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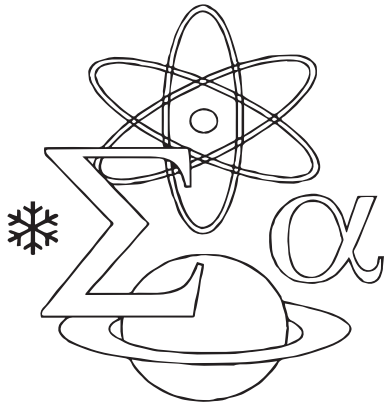

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Aims and Scope

This Journal is a multidisciplinary publication devoted to all field of Natural and Technical Sciences. The Editor of AJNTS invites original contributions which should comprise previously unpublished results, data and interpretations.

Types of contributions to be published are: (1) research papers; (2) shorts communications; (3) reviews; (4) discussions; (5) book reviews;(6) announcements

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SPATIO-TEMPORAL SEISMICITY ANALYSIS ALONG ACTIVE FAULT ZONES IN ALBANIA

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ABSTRACT

A spatio-temporal analysis of seismic activity along the active tectonic fault systems of Albania was conducted in early 2025 employing two diagnostic parameters: the fractal dimension (Dc), which characterizes the heterogeneity,

complexity, and clustering of seismicity, and the standard normal deviate (Z), used to identify precursory seismic quiescence. The magnitude of completeness (Mc) across the Albanian fault zones ranges from 2.5 to 3.4, providing a solid basis for reliable interpretation. The obtained Dc value for the Albanian orogenic belt is 1.93 ± 0.04, indicating pronounced seismic clustering, particularly within the seven major fault zones at both regional and local scales. Seismic quiescence, commonly considered a potential precursor to strong earthquakes, proved effective in detecting anomalous patterns that may signal probable locations of future mainshocks. By integrating Dc and Z analyses, this study reveals structural complexities, seismogenic potential, and quiescence anomalies that go beyond conventional seismicity mapping. These findings enhance understanding of earthquake nucleation processes and support improved assessment of areas susceptible to future moderate-to-large seismic events in Albania.

***Keywords*:** Albanian faults, declustering, seismic quiescence, fractal dimension, seismic hazard

1. INTRODUCTION

Numerous regional and temporal studies have examined the space–time characteristics of earthquake activity worldwide, providing significant insights through the application of scaling laws (e.g., Mogi, 1962; Utsu, 1971; Mandelbrot, 1982; Habermann, 1983; Hirata, 1989; Wiemer and Wyss, 2000; Awad, 2005; Öncel and Wilson, 2007; Öztürk *et al*. 2008; Öztürk, 2011, 2015; Roy *et al*. 2011; Ormeni *et al*. 2017; 2023; Ormeni and Öztürk, 2024).

The Albanian region ranks among the most seismically active areas of the Balkan Peninsula, with numerous destructive earthquakes documented over the past two millennia in historical sources (Sulstarova *et al*. 1980; Aliaj *et al*. 2010; Ormeni and Öztürk, 2024). Situated within the Alpine–Mediterranean seismic belt, Albania accommodates part of the crustal deformation resulting from the collision between the Adriatic microplate and the Eurasian plate (Mazzoli and Helman, 1994).

During the last century, at least seven major earthquakes with magnitudes exceeding Ms 6.0 have affected the region: the 1905 Shkodra earthquake (Ms 6.6), the 1911 Ohrid Lake earthquake (Ms 6.7), the 1920 Tepelena earthquake (Ms 6.4), the 1926 Durrësi earthquake (Ms 6.2), the 1967 Dibra earthquake (Ms 6.7), the 1979 Montenegro earthquake (Ms 6.9), and the 2019 Durrësi earthquake (Ms 6.4) (Kociaj, 1986; Aliaj *et al*. 2010; Ormeni and Öztürk, 2024). More recently, a strong earthquake sequence began with the September 21, 2019 event (M 5.8), culminating

in the November 26, 2019 Durrësi mainshock (M 6.4), located along the Adriatic fault zone approximately 35 km west of the capital city, Tirana (Ormeni and Öztürk, 2024).

This study focuses on the size-scaling characteristics of seismicity in Albania, with particular emphasis on regional, temporal, and magnitude distributions of earthquakes, as well as the parameters of magnitude completeness (Mc), fractal dimension (Dc), and precursory seismic quiescence (Z). All statistical analyses and visualizations, including histograms of regional, temporal, and magnitude distributions, were performed using the ZMAP software (Wiemer, 2001).

2. GEOLOGIC AND TECTONIC STRUCTURES IN AND AROUND ALBANIA

Albania lies within the Alpine-Mediterranean seismic belt and constitutes a convergent tectonic zone between the African and Eurasian lithospheric plates. The principal geological structures of Albania and its surroundings, collectively known as the Albanides, form a segment of the Dinaric–Albanid–Hellenic arc within the broader Alpine orogenic system. The primary source of seismicity in Albania is the ongoing collision between the Adriatic microplate and the Albanian orogen, which generates complex fault interactions and substantial strain accumulation throughout the region. This tectonic regime has produced numerous historical and instrumental earthquakes, including events with magnitudes up to M6.8, such as the 1851 Vlora, 1911 Pogradec, and 1967 Dibra earthquakes, as well as the M7.0 Ulqin earthquake in 1979. More recently, the ML6.4 earthquake in Durres on November 26, 2019 highlighted the persistent high seismic hazard of the region (Öztürk and Ormeni, 2021).

Focal mechanism solutions indicate a predominance of normal and thrust faulting, often accompanied by strike-slip components, reflecting the ongoing convergence between the Adriatic microplate and the Albanian orogen. The coexistence of these faulting styles highlights the complexity of the regional stress field and accounts for the spatial variability in seismic activity observed across different Albanian fault systems. This intricate tectonic framework renders Albania one of the most seismically active areas in the Mediterranean, emphasizing the necessity for detailed monitoring and continuous assessment of earthquake hazard.

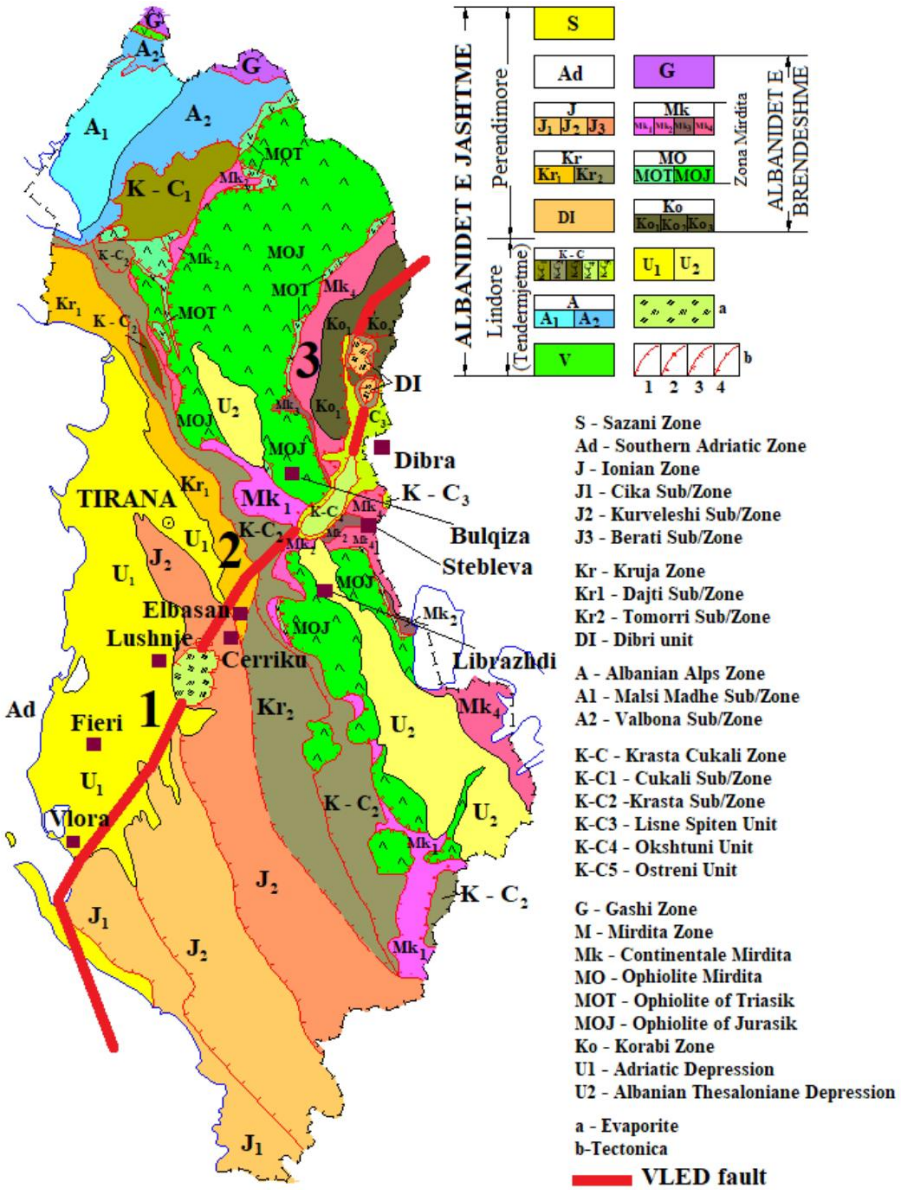

Fig. 1: Schematic tectonic and geologic map of Albania, where further details on the geologic, tectonic, and neotectonic processes in and around the country are provided (Aliaj *et al*. 2010). The internal units comprise the terrains east of the Kruja Zone, while the external units include the terrains of the Kruja, Ionian, and Sazani zones (Aliaj *et al*. 2010).

2. EARTHQUAKE DATA FOR THE TECTONIC FAULT SYSTEMS OF ALBANIA

The earthquake dataset used for this analysis was obtained from the Albanian Seismological Catalogue, and European Mediterranean Seismological Centre (EMSC) catalogue, covering the period from January 17, 1966, to December 31, 2024 (IGEO, 2025). This catalog includes all recorded earthquakes occurring along the Albanian fault zones and their surrounding regions. For the seismic quiescence analysis, the catalog was first declustered. Out of 38,816 earthquakes with ML ≥ 0.1 recorded between 1966 and 2024, a total of 6,254 events (~16.1%) were identified as aftershocks or dependent events and subsequently removed. Assuming a magnitude of completeness of Mc = 2.7, an additional 22,284 earthquakes with ML < 2.7 were excluded. After declustering and completeness filtering, approximately 73.5% of the original catalog (28,538 events) were eliminated, resulting in a homogeneous and uniform dataset of 10,278 earthquakes, which served as the basis for the Z-value seismic quiescence analysis.

The analysis focused on shallow earthquakes (<70 km), as these events are most relevant for seismic hazard assessments and play a crucial role in identifying precursory quiescence anomalies, often associated with major crustal shocks. Focal depth analyses confirm that most earthquakes in the study area occur within the shallow upper and middle crust, consistent with the tectonic framework described previously in (Ormeni, 2010).

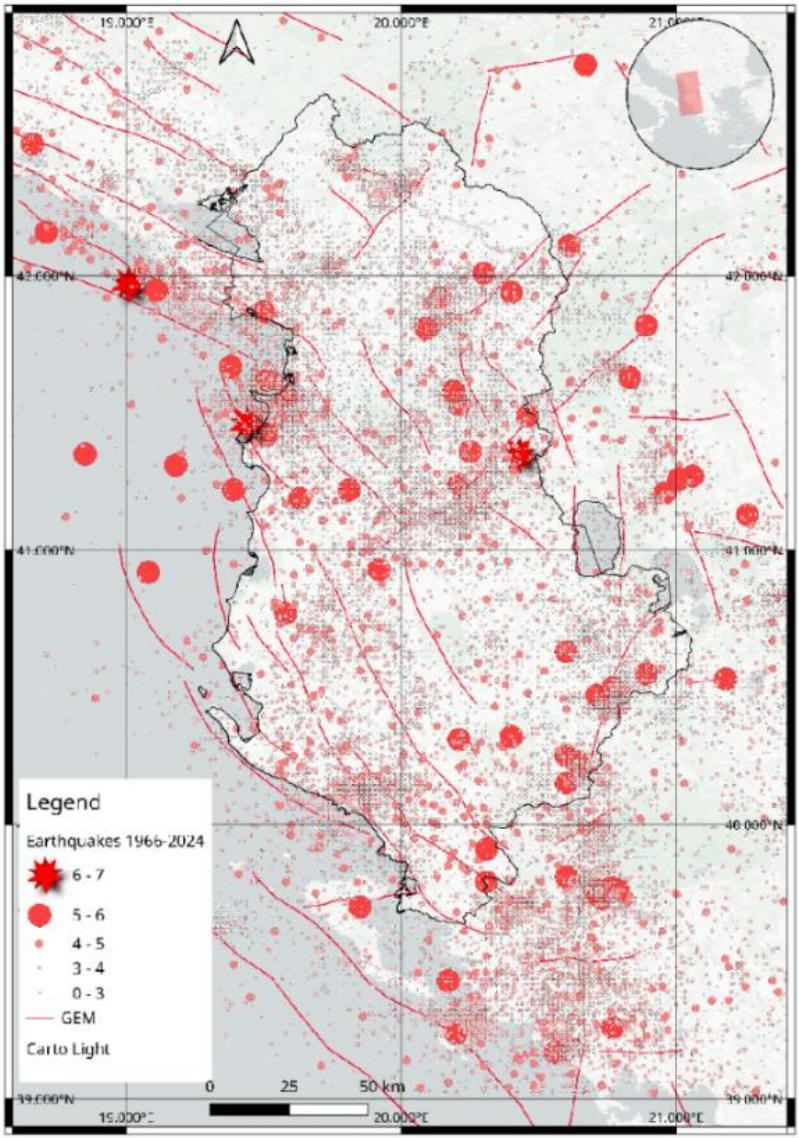

Fig. 2: Epicentral distribution of earthquakes events are displayed with different symbols according to their magnitude ($M_L \geq 0.1$) and for strong mainshocks ($M_L \geq 6.0$, marked with a star) during the period 1966–2024 on the tectonic map provided by GEM.

3. DEFINITION OF ANALYSIS METHODS

In this study, the statistical analyses of seismic activity are restricted to shallow earthquakes with focal depths less than 70 km. This upper depth limit was selected because the seismogenic layer is generally confined to this depth in most tectonic regions worldwide.

Analyses of seismicity, particularly those targeting precursory seismic quiescence, provide valuable insights into the occurrence of major crustal earthquakes and contribute to regional seismic hazard assessment. To investigate earthquake activity along the active tectonic fault systems of Albania, several statistical parameters were evaluated, including histograms of temporal and magnitude distributions, the fractal dimension (Dc-value), and the precursory seismic quiescence (Z-value).

4.1. Seismotectonic (Gutenberg-Richter relation) and Importance of Completeness Magnitude, *Mc*

The frequency-magnitude relationship proposed by Gutenberg and Richter (1944) describes the empirical power-law distribution of earthquake magnitudes and is expressed as:

$$\log_{10} N(M) = a - bM \qquad (1)$$

where *N(M)* is the cumulative number of events with magnitudes greater than or equal to *M* within a given time period, whereas *a* and *b*-values are constants. In studies of frequency-magnitude distributions and precursory seismic quiescence, accurate estimation of the magnitude completeness, *Mc*- is crucial, as using the maximum number of reliable events is essential for obtaining robust results. Because *Mc*-value tends to be higher during the earlier part of a catalog—due to the limitations in detection capabilities—its temporal variation can lead to biased seismicity estimates. Variations in *Mc*-value depend on both the earthquake activity level of the region and the sensitivity and density of the seismic network. Consequently, the accuracy of the precursory seismic quiescence analyses is directly influenced by appropriate determination of the *Mc*-value.

4.2. Fractal Dimension (Correlation Dimension, *Dc*-value)

The fractal dimension quantifies the geometric complexity of a spatial distribution and can vary with both space and time. Fractal analysis is widely used to examine the clustering properties and size scaling

characteristics of earthquake occurrences, under the assumption that earthquake distributions exhibit fractal characteristics. Such analyses are important because they describe the self-similarity and heterogeneity of seismogenic structure. Such analyses are important because they describe the self-similarity and heterogeneity of seismic structures. Among the different methods, of fractal analysis, the correlation dimension (DC)—introduces by Grassberger and Procaccia (1983) through the sphere-counting method—is one of the most commonly applied. The correlation sum *C(r)* and the correlation dimension *Dc* are defined as follows:

$$Dc = \lim_{r \to 0} \left[\log C(r) / \log r \right] \quad (2)$$

$$C(r) = 2N_{R<r} / N(N-1) \quad (3)$$

where $C(r)$ is the correlation function, r is the distance between two earthquake epicenters and N is the number of earthquakes pairs separated by a distance $R<r$. The fractal dimension (Dc) is obtained by fitting a straight line to a log -log plot $C(r)$ versus r. The spatial and temporal fractal characteristics of seismicity provide insights into heterogeneity and complexity of fault systems (Kagan, 2007). Earthquake distributions generally conform to fractal statistics; hence variations in Dc reflect differences in the organization and clustering of seismic activity. Regions with lower Dc values typically correspond to more strongly clustered seismicity, while higher Dc values indicate more spatially uniform distributions. Fractal dimension analysis can also help identify potential seismic gaps, representing unruptured areas along fault systems that may host future earthquakes (Toksöz *et al*. 1979). Therefore, variations in Dc are directly related to the degree of structural complexity and the heterogeneity of stress accumulation within active fault regimes.

4.3. Process for Declustering of Earthquake Data and Standard Normal Deviate Z-Test (Precursory Seismic Quiescence, Z-Value)

Foreshocks, aftershocks, and earthquake swarms can distort the temporal distribution of seismic events, affecting statistical analyses of seismicity. To enable a quantitative assessment of rate changes in earthquake activity, dependent events must be removed from the catalog.

In this study, dependent events were identified and excluded using the Reasenberg (1985) declustering algorithm, as implemented in the ZMAP software (Wiemer, 2001). The resulting declustered catalog containing

10,278 independent earthquakes, was then used for the analysis of precursory seismic quiescence (Z-value).

A spatial grid of 0.1° × 0.1° in latitude and longitude was applied to the study area. The ZMAP method was used to detect regions exhibiting quiescence anomalies, while the standard normal deviate (Z-test) was employed to evaluate their statistical significance. This method calculates the Log Term Average, (LTA(t)), which expresses the degree of quiescence in terms s of standard deviations:

$$Z(t) = \frac{R_{all} - R_{wl}}{\sqrt{\frac{\sigma^2{}_{all}}{n_{all}} + \frac{\sigma^2{}_{wl}}{n_{wl}}}} \qquad (4)$$

where R_{wl} is the mean earthquake rate within the foreground window, R_{all} is the average rate over the entire background period, σ represents the standard deviations, and n is the number of samples, within and outside the window, respectively. The Z-value is estimated as a function of time by allowing the foreground window slide along the catalogue's time series. The resulting time dependent function, denoted LTA (t), enables the detection of periods of seismic quiescence that may precede large earthquake events.

4. Results of Statistical Investigations of Recent Seismicity and Discussions

A statistical evaluation of recent earthquake activity along the active tectonic fault systems of Albania was conducted basing on the fractal dimension (Dc-value), the standard normal deviate (Z-value), and regional, temporal, and magnitude histograms covering the period 1964–2024. The fractal dimension provides insight into the complexity and clustering patterns of earthquake occurrences, while the Z-helps detecting precursory seismic quiescence anomalies prior to major shocks. Together, these parameters provide important perspectives for assessing future seismic hazards in the region. Figure 3a presents the cumulative number of earthquakes over time for both the original and declustered catalogs. Between 1966 and 1975, seismicity remained relatively stable, followed by only a few events from 1975 to 1979. A notable increase in earthquake activity occurred between 1979 and 1995 and continued through 2019, with a significant rise in the number of events observed between 2019 and

2023.Figure 3b illustrates the temporal variation of the magnitude of completeness (Mc-value). The original catalog comprises 38,816 earthquakes with $M_L \geq 0.1$. As noted earlier, the magnitude of completeness (*Mc*-value) is a critical parameter for analyzing precursory seismic quiescence. Accordingly, *Mc* was estimated as a function of time using the maximum curvature method within a moving-window approach. Specifically, *Mc*-values were calculated for samples of 2000 earthquakes per window. Because *Mc* exhibits temporal variability, the number of events per window was maximized to ensure robust statistical evaluations (Fig. 3b). Temporal variations in *Mc* were further examined using standard deviations computed over 100-event moving windows. Mc remained between 2.5 and 3.4 until 2019, after which it decreased to approximately 2.5 by the end of that year. Between 2019 and 2023, *Mc* fluctuated within the range 1.5–2.8. Over the longer interval of 1967–2019, Mc varied significantly between 2.5 and 3.5. Based on these findings, an average *Mc*-value of 2.8 was adopted for all subsequent statistical analyses.

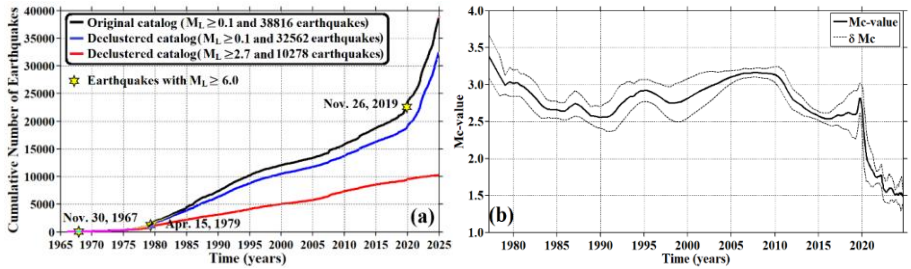

Fig. 3: (a) Time variations of the cumulative number of earthquakes between 1966 and 2024 for the catalog with $M_L \geq 0.1$ and the declustered catalog with Mc ≥ 2.7. **(b)** Temporal variation of magnitude completeness (Mc-value). The standard deviation, δMc, is also indicated.

As described in the *Data* section, the earthquake catalog comprises events with magnitudes ranging from 0.1 to 6.9, with the largest event corresponding to the 1979 Ulqin earthquake (M_L = 6.9). Accordingly, a value of ML = 7.0 was selected as the upper limit for the magnitude axis. A key outcome of the declustering process is the removal of dependent events, resulting in a more reliable, robust, and homogeneous dataset.

Figure 4a presents the time histograms of seismic events in Albania and its surrounding regions for the period 1966 to 2024. Seismic activity remained relatively low between 1966 and 1974, with only 329 recorded events. Between 1975 and 2002, earthquake occurrences increased

substantially, reaching a total of 12,537 events, followed by 8,327 events between 2003 to 2018. A pronounced increase is observed after 2018, with 17,640 earthquakes recorded during the period 2019-2024.

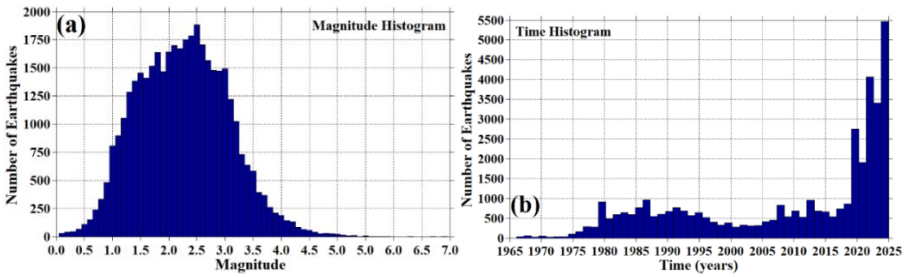

Fig. 4: (a) Time histogram of seismicity in Albania and its surroundings from 1966 to 2024. **(b)** Magnitude histogram.

Figure 4b presents the magnitude histogram of seismic events within and around the Albanian fault zones. As noted in the Data section, earthquake magnitudes range from 0.1 to 6.9, with the frequency of events exhibiting a typical exponential decline as magnitude increases.

Most earthquakes have magnitudes between 1.0 and 3.5, with the highest frequency at ML = 2.5. Specifically, 31,062 earthquakes fall within the range $0.1 \leq ML < 3.0$, 6,912 events within $3.0 \leq ML < 4.0$, 777 events within $4.0 \leq ML < 5.0$, 62 events within $5.0 \leq ML < 6.0$, and only 3 events within $ML \geq 6.0$. These results indicate that small-to-moderate earthquakes (ML 1.0–3.5) occur far more frequently than larger events in Albania and its surroundings. The high frequency of small earthquakes may reflect increasing stress accumulation along the Eastern Fault Zones (EFZ) in recent years.

The correlation dimension (*Dc*-value) of earthquake epicenter distributions within Albania's active tectonic fault systems was then calculated by fitting a straight line to the curve of the correlation integral, C(R), versus distance, R. *Dc*-values were determined with 95% confidence limits using linear regression (Fig. 5). For the entire study region, the Dc-value was found to be $Dc = 1.93 \pm 0.04$, with a well-defined linear scaling range between 5.02 and 208.21 km (Fig. 5). Standard deviations of Dc-values were also estimated within this distance range. As previously discussed, the fractal dimension provides valuable insight into the spatial organization of seismicity, since earthquake distributions typically exhibit fractal characteristics. Higher *Dc*-values are generally associated with active and structurally complex fault systems (Öncel and Wilson, 2002),

whereas lower values characterize regions where earthquakes are clustered due to isolated asperity failures (Barton *et al*. 1999). Therefore, the relatively high *Dc*-values observed in this study likely reflect the dominant structural properties of the Albanian fault systems and the clustering of seismic activity. Because a uniform distribution decreases with increasing clustering, these high *Dc*-values may also indicate spatial variations in stress distribution across the region.

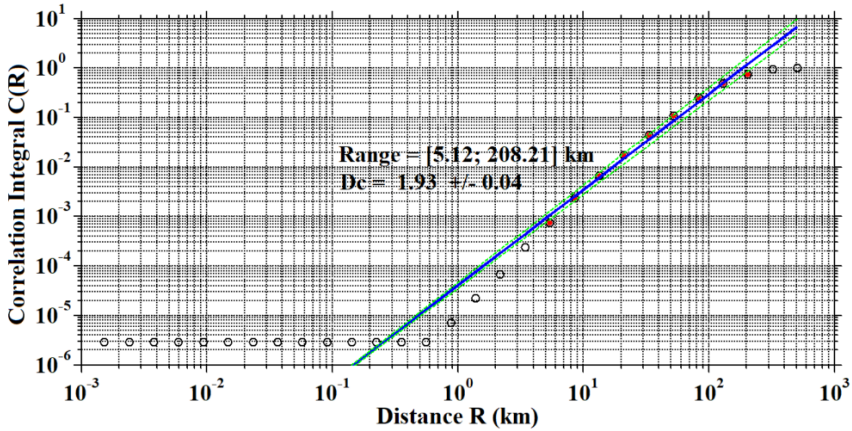

Fig. 5: Fractal dimension (Dc-values) for the Albanian fault zones. The slope of the blue line represents Dc-values. Dashed lines indicate standard deviations.

As shown in Figure 6, the regional variations of the standard normal deviate (Z-value) along Albania's active tectonic fault systems are mapped for early 2025. The interpretation of Z-values is straightforward: low Z-values indicate statistically insignificant changes in earthquake activity, whereas high Z-values correspond to a reduction in seismicity rate, often interpreted as precursory quiescence.

When compared with earlier studies (e.g., Öztürk and Bayrak, 2012; Öncel & Wilson, 2007; Award *et al*. 2005), the patterns obtained here are consistent with the general observation that quiescent periods may precede major seismic events in regions of high strain accumulation. However, the present analysis extends these interpretations by providing a quantitative spatial mapping of Z-value anomalies within the specific tectonic framework of Albania.

The regional distribution of Z-values for the Albanian fault systems is presented in Figure 6. Seven anomalous regions (A–G) exhibiting significant seismic quiescence were identified:

A: Shkodër–Bajram Curri transversal fault zone, northern Albania (42.00°N, 19.50°E – 42.35°N, 20.10°E), encompassing the Curraj i Epërm–Rragam–Theth fault zone.

B: Skavica–Kukës–Prizren transversal fault segment, part of the Kurbnesh–Kukës–Prizren fault zone, northeastern Albania, extending into Kosovo (41.90°N, 20.35°E – 42.25°N, 20.70°E).

C: Cerje–Prespa–Bitola fault zone, extending into North Macedonia near the Albanian border (40.75°N, 20.95°E – 41.00°N, 21.25°E).

D: Elbasan–Bene–Kostenj fault segment, central portion of the Vlora–Lushnje–Elbasan transversal fault zone (41.10°N, 20.10°E – 41.35°N, 20.30°E).

E: Vjosa River estuary–Fier–Lushnjë fault segment, southern portion of the Vlora–Lushnje–Elbasan transversal fault zone (40.65°N, 19.30°E – 40.90°N, 19.70°E).

F: Kudhes–Kuç–Vermik fault zone (40.10°N, 19.80°E – 40.30°N, 19.75°E).

G: Selo–Dhrovjan–Lazarat fault segment, part of the Selo–Rabie fault zone, including the Libohovë–Poliçan zone (39.85°N, 20.35°E – 39.95°N, 20.45°E; 40.00°N, 20.25°E – 40.10°N, 20.35°E).

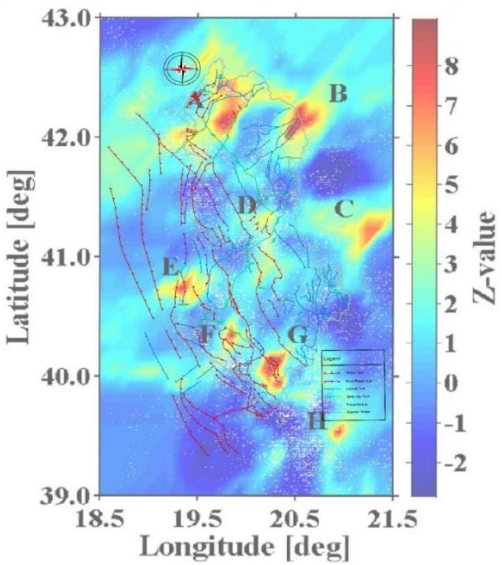

Fig. 6: Changes in Z-values at the beginning of 2025 (Tw = 4.5 years) for the updated active tectonic fault systems map of Albania. White dots represent declustered events with $M_L > 2.7$.

Previous studies (Katsumata and Kasahara, 1999; Chouliaras and Stavrakakis, 2000; Polat *et al*. 2008; Öztürk, 2013; Öztürk and Bayrak, 2012; Ormeni *et al*. 2017; Öztürk and Ormeni, 2021) have demonstrated that seismic quiescence often precedes major earthquakes in various parts of the world. Therefore, the quiescence anomalies observed in different segments of Albania's active fault systems may be significant and could potentially indicate the locations of future large earthquakes.

Using the maximum likelihood approach to estimate the LTA(t) function to map *Z*-values, these studies showed that regions with larger *Z*-values can be interpreted as potential nucleation zones for forthcoming major earthquakes. Similar methodologies were applied by, Polat *et al*. (2008), Öztürk (2011), Öztürk and Bayrak (2012), and later by Ormeni and Öztürk (2017; 2024), Öztürk and Ormeni (2021) to various tectonic regions of Turkey and Albania, yielding meaningful results. For instance, significant seismic quiescence anomalies were detected before the 8 March 2010 Elazığ and 23 October 2011 Van earthquakes in eastern Turkey, as well as prior to the 26 November 2019 Durrës earthquake in western Albania These findings confirm that these statistical parameters can play an important role in identifying potential sites of future seismic activity. In summary, the combined analysis of *Dc*-value and *Z*-value provides a robust framework for seismic hazard assessment. The identification of high *Dc*-values and pronounced quiescence anomalies in several regions of Albania at the beginning of 2025 suggests that these anomalous zones warrant special attention in the evaluation of earthquake potential along the country's active tectonic fault systems.

5. CONCLUSIONS

This study presents a temporal and regional statistical analysis of recent earthquake activity along Albania's active tectonic fault systems. Several key parameters were applied—namely, the correlation dimension (Dc-value), precursory seismic quiescence (Z-value), and regional, temporal, and magnitude histograms—to evaluate earthquake clustering patterns and seismic hazard potential. The overall Dc-value of 1.96 indicates significant clustering of earthquake activity at both small and large spatial scales.

The Z-value mapping for 2025 revealed several notable quiescence anomalies distributed across seven regions (A–G) along Albania's active fault systems, including the Shkodër–Bajram Curri, Skavica–Kukës–

Prizren, central and southwestern segments of the Vlora–Lushnje–Elbasan fault zone (VLED), Kudhes–Kuç–Vermik, Selo–Dhrovjan, Libohovë–Poliçan fault zones, and the Cerje–Prespa–Bitola fault zone near the Albanian border.

The integrated application of Dc-value and Z-value provides valuable insight into earthquake clustering, stress accumulation and potential future seismic activity. The observed quiescence anomalies, in combination with the statistical characteristics of the earthquake distributions, contribute to the improving seismic hazard assessment and may help forecast the probable locations of the earthquakes in Albania's most active tectonic regions.

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Declarations

Data accessibility (websites, platforms): www.geo.edu.al, EMSC-CSEM.org

Declaration of AI use: There has been no use of AI when writing the actual paper.

Author Contributions

RrO – Conceptualization; compilation and cleaning of the earthquake catalogue; tectonic interpretation; writing – original draft preparation; writing – review & editing; coordination of the Albania-focused seismotectonic framework; SÖ– Gümüşhane University, Department of Geophysics, Türkiye Methodology; statistical analysis; ZMAP processing; fractal dimension and Z-valueanalysis; validation; writing – methodology section; LP –Tectonic framework evaluation; interpretation of active fault systems; integration of neotectonic models; critical revision of geological sections, IH –Data processing; spatial analysis of epicentral distributions; preparation of tectonic and seismotectonic maps; EV-Expert evaluation of structural geology; review of tectonic map interpretations; integration of regional fault kinematics; PDiM–Review of geologic data consistency; contribution to the interpretation of crustal deformation and fault segmentation; NP –Contribution to regional seismicity assessment in northeastern Albania and Kosovo; catalog cross-checking; revision of

temporal analyses; DM and OGj- Technical support; dataset verification; GIS preparation of maps; assistance in visualization and figure design

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MIGRATING EARTHQUAKE SEQUENCES ON MAJOR FAULT SYSTEMS IN SOUTHERN AND EASTERN ALBANIA (1851- -1942)

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ABSTRACT

Albania is located within the complex tectonic framework of the external Dinarides and Hellenides, where multiple active fault systems accommodate ongoing crustal shortening. However, significant uncertainties persist regarding fault segmentation, kinematics, and surface expression. This study integrates tectonic geomorphology, field observations, and historical data to reassess the relationships between active structures and destructive seismicity in southern and eastern Albania during the period 1851 to 1942. Remote sensing data (satellite

imagery and digital terrain models (DTM)), high-resolution topographic data, and field surveys were combined with earthquake catalogues and focal-mechanism datasets to identify and evaluate seismogenic sources in two representative case studies. The first case concerns the Vlora–Elbasani Line and the southern frontal thrust system of the Ionian Zone, which produced a prolonged seismic sequence including more than twelve Mw > 6 earthquakes, culminating in the 1930 event. This sequence is interpreted as a migrating rupture process that facilitated the thrusting of the Ionian Zone over the Sazani Zone. Detailed analysis of the 1897 Dhiver earthquake reveals well-documented coseismic ruptures and highlights the persistence of oral traditions that preserve seismological memory. The second case study focuses on eastern Albania (1894-1942), where strike-slip deformation along the Peshkopi–Bilisht fault system is associated with pull-apart basins and major historical earthquakes within the Ohrid graben.

Keywords: Active faults, historical seismicity, seismotectonics, migrating earthquake sequences, crustal deformation, Albania

1. INTRODUCTION

Albania, located within the complex deformational framework of the external Dinarides and Hellenides, hosts numerous active fault systems that primarily accommodate southwest-directed crustal shortening. However, significant uncertainties remain regarding the surface expression, segmentation, and seismogenic potential of many of these faults. Although instrumental seismicity provides valuable constraints on the recent activity of certain structures, the historical earthquake record, when critically reassessed in the context of fault geometry, past surface ruptures, and regional tectonics, offers additional and often essential constraints for identifying and characterizing seismogenic sources. The data presented in this study were collected within the framework of the Scientific Cooperation Agreement between the National Research Council of Italy (CNR) and the Ministry of Education and Sports of the Republic of Albania, entitled "*Earthquakes, active tectonics and seismogenic sources in Albania*" (2021-2022). This initiative involved multiple Italian and Albanian institutions, including the Institute of Geosciences and Earth Resources (CNR), the Geological Survey of Italy (ISPRA), Institute of Geosciences of the Polytechnic University of Tirana, Academy of Sciences of Albania, Albanian Geological Survey (EATA project, https://seismotectonics-albania.com). Additional results from the same framework are presented in this volume by Di Manna *et al*. (2025), who

focus on the active tectonics of the central seismotectonic province, and by Vittori *et al*. (2025), who describe the new integrated earthquakes catalogue developed within this collaborative project.

Migrating earthquake sequences are spatiotemporal patterns in which seismicity propagates systematically along a fault, or through a network of faults, over time. This migration is typically driven by static stress transfer from preceding events, pore-fluid diffusion, or aseismic slip transients. As strain accumulates on faults, rupture occurs when rock strength is exceeded, releasing stored elastic energy. The initial rupture not only relieves stress locally but also redistributes stress to adjacent fault segments or nearby faults, either promoting or inhibiting subsequent failure. When stress transfer promotes failure, it may generate a cascade of earthquakes in which one event triggers another (e.g. Mogi, 1968; Bonini *et al*. 2016). This process— variously termed migrating earthquake sequences, earthquake triggering, or static and dynamic stress transfer—is widespread in active tectonic regions. A classic example is the 1939-1992 earthquake sequence along the North Anatolian Fault, where ten major earthquakes with magnitude exceeding 6.7 ruptured approximately 1.000 km of the fault system over six decades (e.g., Stein *et al*. 1997). In this sequence, nine of ten major earthquakes occurred on fault segments brought closer to failure by stress transfer from preceding ruptuers. Similar behaviour was observed during the 2016 central Italy earthquake sequence (e.g., Pizzi *et al*. 2017) and the Turkey 2023 earthquake sequence (e.g., Núñez-Jara *et al*. 2025), although progressive fault failure may also occur at local scale (Fischer *et al*. 2023). Recognizing and modelling progressive rupture is therefore essential for seismic hazard assessment, as it helps to identify where future large earthquakes may occur and to estimate possible rupture lengths and maximum magnitudes. This approach also aids in identifying possible seismic gaps, that is segments of active fault systems known to produce significant earthquakes that have not slipped in an unusually long time compared with other segments along the same structure, considered likely to produce large shocks during the next few decades (e.g., Lay and Nishenko, 2022, and references therein).

In this study, we present two case histories from the southern and eastern seismotectonic provinces of Albania for the period 1851-1942. These examples illustrate how active fault systems, defined through remote sensing, morphotectonic analysis, and field observations, correlate with major historical earthquakes and provide insight into the interaction of seismic sources. The attribution of large earthquakes to mapped faults

is based on both spatial relationships and on documented coseismic effects described in historical reports. Earthquake magnitudes, locations, and uncertainties were homogenized in the integrated Earthquake Catalogue of Ormeni *et al*. (2022) and Vittori *et al*. (2025), from which the seismic data in this study are derived. The analysed case studies provide clear evidence of the progressive rupture process in the development of earthquake sequences, emphasizing their importance for seismic hazard analysis and the design of effective risk mitigation strategies. They also contribute to a better understanding of active deformation and regional geodynamics in the broader Alpine–Dinaric–Hellenic region, particularly regarding the interaction between the Ionian Zone and the Sazani Zone (Adria) (e.g., Mantovani *et al*. 2023).

The overall objective of this work is to present an integrated analysis of selected active faults as case studies in order to develop a workflow applicable at both national and local scales. Based on a multidisciplinary approach, this workflow enhances the interpretation of major active tectonic zones and their relationship to seismicity, enabling the assessment of the seismic potential, fault interconnections, and the identification of seismic gaps and areas of elevated future seismic hazard.

These case studies provide concepts and methodologies that can support the development of a much-needed future national seismotectonic synthesis for Albania. Updating the active-fault and characterizing seismic sources using new data and modern analytical approaches are fundamental for producing an improved seismotectonic framework, which is essential for more reliable seismic-risk assessment and safer land-use and urban-planning strategies.

2. MATERIALS AND METHODS

The NW-SE trending Albanides represent a typical fold and thrust belt system (De Celles and Giles, 1996) characterized by a west-verging thrusting over the Apulia-Adriatic foreland. Based on variations in tectonic style, as well as in the rate and timing of deformation along the vergence direction, three different geological units are distinguished (Aliaj, 2006; Velaj, 2015): i) Apulia-Adriatic foreland, ii) the Albanides orogen, and iii) the peri-Adriatic depression. The review of active tectonics of Albania presented here builds upon a critical appraisal of published literature combined with original investigations.

The structural-geomorphological analysis is based on the premise that active faults intersecting the topographic surface generate ground ruptures, producing characteristic landforms that accumulate over time and leave persistent geomorphic signatures. The degree of preservation or sharpness of these morphological features is commonly interpreted as an indicator of their relative recency. Our approach integrates tectonic geomorphology and structural geology through the analysis of remote sensing imagery and digital terrain models at multiple spatial scales, targeted field mapping in key areas, and geological information derived from the literature, with the aim of identifying features of tectonic significance. Where possible, the mapped faults were checked directly in the field along their most accessible traces in search of evidence of Late Quaternary or historical co-seismic ruptures. This approach has been successfully applied also in Albania, in the context of both active normal and reverse faulting (Hoffman *et al*.2010; 2012; Biermann *et al*. 2019, 2021; D'Agostino *et al*. 2022; Aliaj and Mesonjesi, 2023).

The morphotectonic study was conducted at the regional scale, through the interpretation of satellite imagery (Google Earth) and digital terrain models (DTM) with spatial resolution of 30 m (ALOS 3D World, SRTM) and 10 m (COPERNICUS EU-DEM). At the local scale, higher-resolution topographic maps and orthophotos available via Web Map Services (WMS) from Albanian geportals (http://geoportal.asig.gov.al/map/?auto=true and http://www.gsa.gov.al/en) were analysed, complemented by targeted field surveys. At specific sites (e.g., Dhiver; see Section 3.1.1.), high-precision drone-based photogrammetry was used to image and quantify fault scarps in detail.

From a seismological perspective, a first step consisted of homogenizing the various earthquake catalogues compiled for Albania and neighbouring regions into a single integrated dataset (Ormeni *et al*. 2022; Vittori *et al*. 2025). A similar integration and homogenization procedure is currently being applied to develop a unified focal-mechanism catalogue. These datasets have been further updated with additional information from 2023–2024. Particular attention was devoted to the critical revision of historical earthquake reports describing coseismic surface ruptures along major active faults and other associated coseismic phenomena.

Based on the integration of these datasets, ground ruptures described in the contemporary sources as particularly significant—showing lateral continuity along strike and located within the epicentral areas of strong

earthquakes—were interpreted as the surface expression of seismic ruptures at depth and were associated with the corresponding active faults.

3. RESULTS AND DISCUSSION

The results of this study were synthesised into a preliminary map of potential capable faults and fault systems of Albania, compiled using QGIS (Fig. 1). In the following sections, we present two representative examples of fault systems characterized by ongoing seismicity and well-defined kinematics in the southern and eastern Albanides, with particular emphasis on their possible structural linkages and progressive activation.

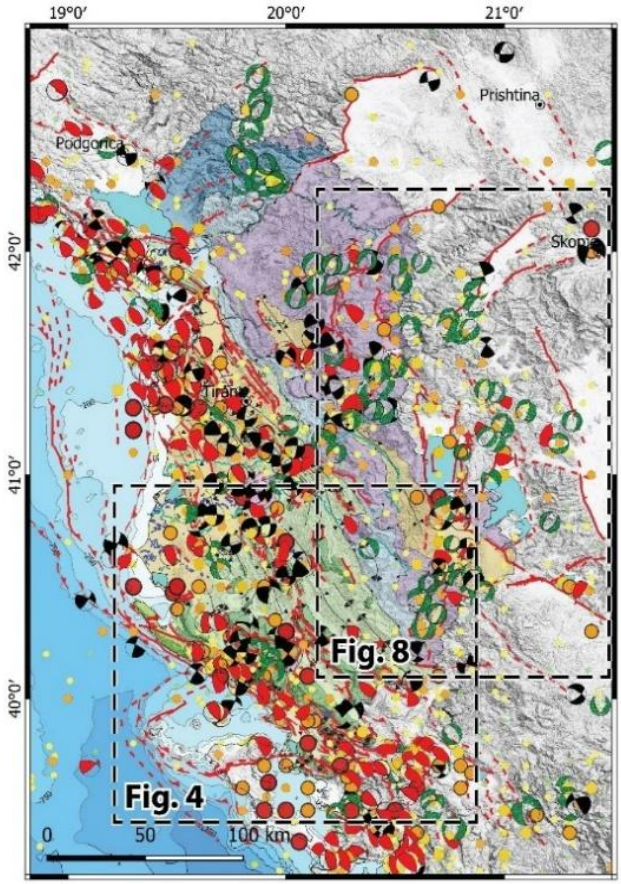

Fig. 1: Schematic map of active fault systems, earthquakes and focal mechanisms of Albania.

3.1. Vlorë-Elbasan Line and frontal thrust system of the Ionian Zone (1851 to 1930)

The N50°E- trending crustal structure known as the Vlora-Elbasani-Dibra Line, hereinafter referred to as the Vlora-Elbasani Line (VEL), is recognised as one of the most hazardous active fault systems in Albania. The VEL is characterized by predominantly oblique normal-dextral movement (Sulstarova *et al*. 2000).

The fault zone is exposed in a quarry NE of Kanina, where the fault plane strikes 325° and dips 75° toward the northwest (Fig. 2). Slickensides preserved on the fault surface indicate normal-dextral oblique slip, with a rake of approximately 135°. Also crops out outside the quarry, the fault plane can also be traced at the base of the cumulative fault escarpment (Figs 2B and 2C). In this southern sector, the normal component of motion along the VEL, which contributed to the development of the peri-Adriatic basin, is expressed by a large NW-dipping monocline south of Selenica. The structure reflects the tilting of the Pliocene-Pleistocene deposits associated with basin subsidence (Fig. 3).

In 1851, the VEL generated a destructive seismic sequence comprising five earthquakes with M > 6 earthquakes occurring in the same year, three of which took place within an interval of 8 days (Vlora on October 12, Mw 6.6/6.82, Elbasani on October 17, Mw 6.6, and Berati on October 20, Mw 6.1) (Fig. 4A). This sequence was preceded by an Mw 6.3 earthquake near Elbasani on January 20 and followed by an Mw 5.74 event near Berat on 29 December. Together, these events indicate progressive rupture along the fault system. Seismic activity continued in Vlora area in 1859 and 1862, with two earthquakes of Mw 6.1, culminating in the strong earthquakes of 1866. During that year, a sequence of three major shocks (Mw 6.6, 6.24 and 5.89) struck the region over a two-month period (January 2, February 28 and March 2, respectively) (Figs 3 and 4B), producing extensive surface faulting between Vlora and Kanina.

Mihailovic (1927) referred to the 1866 earthquake as "*the Seventh destruction of Vlora and Kanina* If this expression is interpreted as referring to the destructive events over the past two millennia, it would imply an average recurrence interval of approximately 285 years. This estimate is consistent with the timing of the previous strong earthquake documented in the Vlora area on April 26, 1601 (Mw 6.6), which occurred roughly 250-265 years before the 1851-1866 seismic sequence.

Fig. 2: (**a**) The Vlora fault zone near the surface. (**b**) Cumulative fault scarp. (**c**) Vlora fault plane cropping out at the base of the scarp, where it reaches the topographic surface.

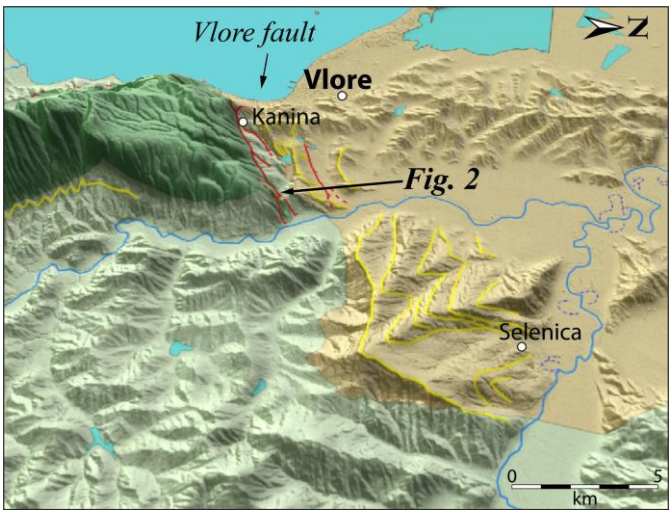

Fig. 3: Perspective view toward the southwest on the Vlora fault and the monocline at Selenica.

The southern frontal thrust system of the Ionian Zone, extending between Borshi (Albania) and Paramythia (GR), was also activated during a seismic series lasting several years, with major earthquakes occurring in 1893, (Mw 6.62), in 1895 (two events of Mw 6.2 and Mw 6.8), and in 1897 (Mw 6.2 and Mw 6.58) (Fig. 4C). Although surface faulting is clearly

documented only for the 1897 event, the entire sequence is consistent with the activation of the frontal thrust belt, here referred to as the Maja e Frasherit thrust front, after its most prominent topographic expression.

Seismic activity resumed in 1920, concentrating in Tepelena and Vlora regions. On November 26, 1920**,** an Mw 6.2 earthquake almost completely destroyed the town of Tepelena, caused severe damage to villages along the Shkumbini River valley, from Adalit to Pekini including Bença, Turani, Dhemblani, Memaliaj, Kashishti, Salari, Dragoti, and Luzati. On 18 December 1920**,** a further earthquake (Mw 5.6) struck Vlora and also damaged Elbasani. The epicenter of this event was located offshore (40.5N, 19.5E), and it generated a tsunami in the Gulf of Vlora that flooded Sazani Island and inundated extensive coastal areas, resulting in numerous fatalities (Morelli, 1942).

The two fault systems described above —the Vlora-Elbasani Line and the southern frontal thrust system are not independent structures. Instead, they form part of a single major fault system that defines the margin of the Ionian Zone thrust pile, which overthrusts the Sazani Zone. The 1930 earthquake effectively filled the seismic gap between Borshi and Vlora along this margin (Fig. 4D). Despite the complexity of the event, historical descriptions of the earthquake effects and ruptures (Novack, 1931, 1933) allow the identification of the principal coseismic faulting, which corresponds spatially to this previously unruptured segment.

Overall, the available evidence suggests that a complete earthquake cycle unfolded over a period of 79 years (1851 - 1930), during which more than twelve earthquakes with M > 6 activated a fault system exceeding 250 km in length, extending from Elbasani to Paramythia. This progressive activation likely accommodated a discrete increment of thrusting of the basal fold-and-thrust system of the Ionian zone over the Sazani Zone (i.e., Adria) (Fig. 4E). Within this framework, the Vlora-Elbasani Line (VEL) functions as a major tear fault within the thrust pile, characterized by a right-lateral component of slip and downthrow of the northwestern block, at least southwest of the Dumrja salt diapir. The right-lateral displacement along this structure also offsets the main seismically active frontal thrust belt of Albania (Fig. 1).

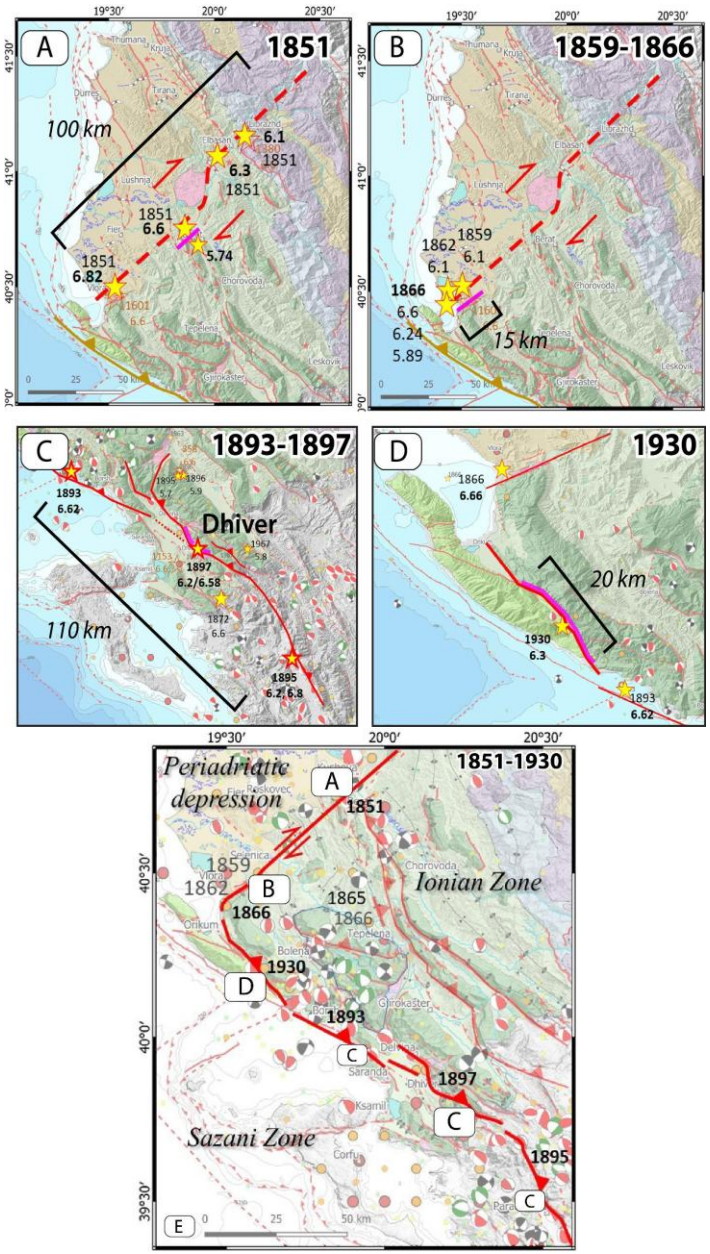

Fig. 4: Relevant earthquakes along the VEL and southern front of the Ionian zone: (**a)** 1851, (**b**) 1866, (**c**) 1893-1897, (**d**) 1930. In purple the relative co-seismic surface ruptures. (**e**) Summary diagram of the 1851-1930 seismic cycle, allowing the thrusting of the Ionian Zone over the Sazani Zone (Adria).

3.1.1. Dhiver earthquake, 1897

The Dhiver earthquake of 17 January 1897 (Mw 6.2-6.58) is examined in detail as a representative case study, as the coseismic ruptures associated with the event are not only well documented in contemporary sources but are also preserved in the collective memory of the local population.

Agamennone (1897), the primary contemporary source, compiled information obtained from local eyewitness accounts (Albini and Stucchi, 1997). Although Agamennone reports the date as 15 January, the event is consistently listed as January 17 in subsequent catalogues.

The earthquake was strongly felt in Saranda and Delvina and the near-complete destruction of the mountain village of Dhiver (Fig. 5). Severe damage was also reported in localities located within approximately 15 km of the epicentral area, including Koukouratés or Kullurice, Cerkovice and Navarice (Albini and Stucchi, 1997) (Fig. 5B). Despite the detailed historical documentation, there remain contrasting interpretations regarding both the epicentral location and the magnitude of the event. Sulstarova *et al*. (1972) initially placed the epicenter at Dhiver, whereas Sulstarova and Kociaj (1975) later relocated it closer to Delvina. In the European Pre-instrumental Earthquake Catalogue EPICA (Rovida *et al*. 2022), the epicentre is positioned near the Greek border, approximately 15 km south of Dhiver. Based on the spatial distribution of damage and documented coseismic effects, we consider the most plausible location to be at or near Dhiver, along the same frontal thrust system activated during the 1893 and the 1897 earthquakes (Fig. 4C). The magnitude is estimated at 6.58 in the EPICA catalogue and at 6.2 in Papazachos *et al*. (2010); the latter estimate appears more consistent with the spatial distribution and intensity of observed effects. Given the limited extent of both the epicentral and damage areas, the earthquake was likely characterized by a relatively shallow focal depth.

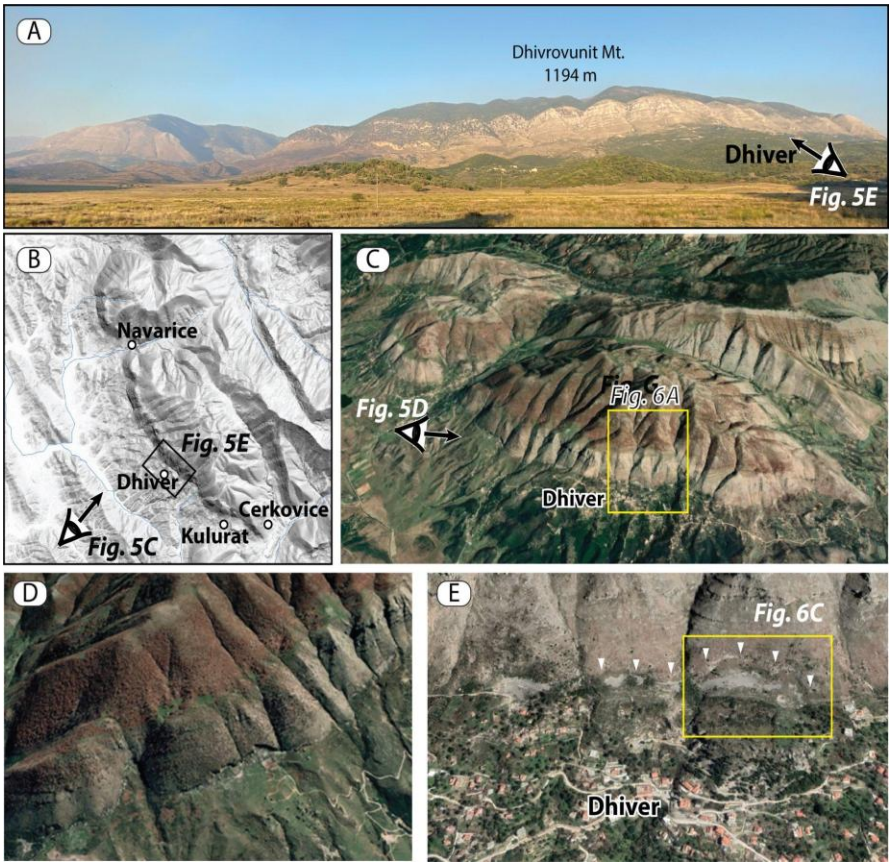

Fig. 5: (**a**) Panorama on the Dhiveri thrust front toward the southwest. (**b**) DEM of Dhiveri thrust area. (**c**) Perspective view toward NE of the fault generated mountain front. (**d**) Thrust front and fault scarp between Dhiveri and Navarica. (**e**) Seismic rupture of the 1897 earthquake at the base of the faceted slope (white triangles).

Coseismic ground ruptures were described in a contemporary local newspaper (*Le Moniteur Oriental*; Agamennone, 1897):

> " … *La montagne de Divri a été fendue en plusieurs endroits et des crevasses sortaient des flammes et de la fumée*" ["The mountain of Divri was split in several places, and flames and smoke were coming out of crevasses"].

Sulstarova *et al.* (1972) further note:

> "*This village* [Dhiver] *was completely destroyed. There were cracks in the ground up to 15 cm wide, in root (limestone) rocks.*

> […] *many aftershocks, which lasted for 7-8 months. In the vicinity of the epicentral area (Dhiver mountain), tremors were felt every 10-30 minutes during the first month.*"

During a field survey conducted on October 4, 2021, we interviewed a local resident, Mr. Spyros Saqellaris (born in Dhiver in 1947), who spontaneously provided the following oral testimony. According to his grandfather, the earthquake of 1897 produced three distinct ground steps at Dhiver extending from the base of the mountain slope down to the square of the present-day village. At that time, the settlement also occupied the area at the foot of the slope [the ruins of several houses can still be seen]. The highest rupture can still be seen at the foot of the mountain [Mr. Saqellaris identified these traces with the rock "scarplet" that we had observed at the base of the triangular facets], the lowest rupture passed through the square of the present-day village. The houses at the foot of the slope were abandoned on that occasion, and the people moved to the present-day village.

The details reported in this oral account are consistent with our geomorphological observations and structural interpretations, thereby supporting the attribution and dating of the surface rupture to the 1897 event (Figs 5 and 6). Owing to the clarity of the description and the precision of the locations indicated, this testimony constitutes a reliable account of significant seismological value and shows how oral tradition can preserve detailed memories of major seismic events across generations.

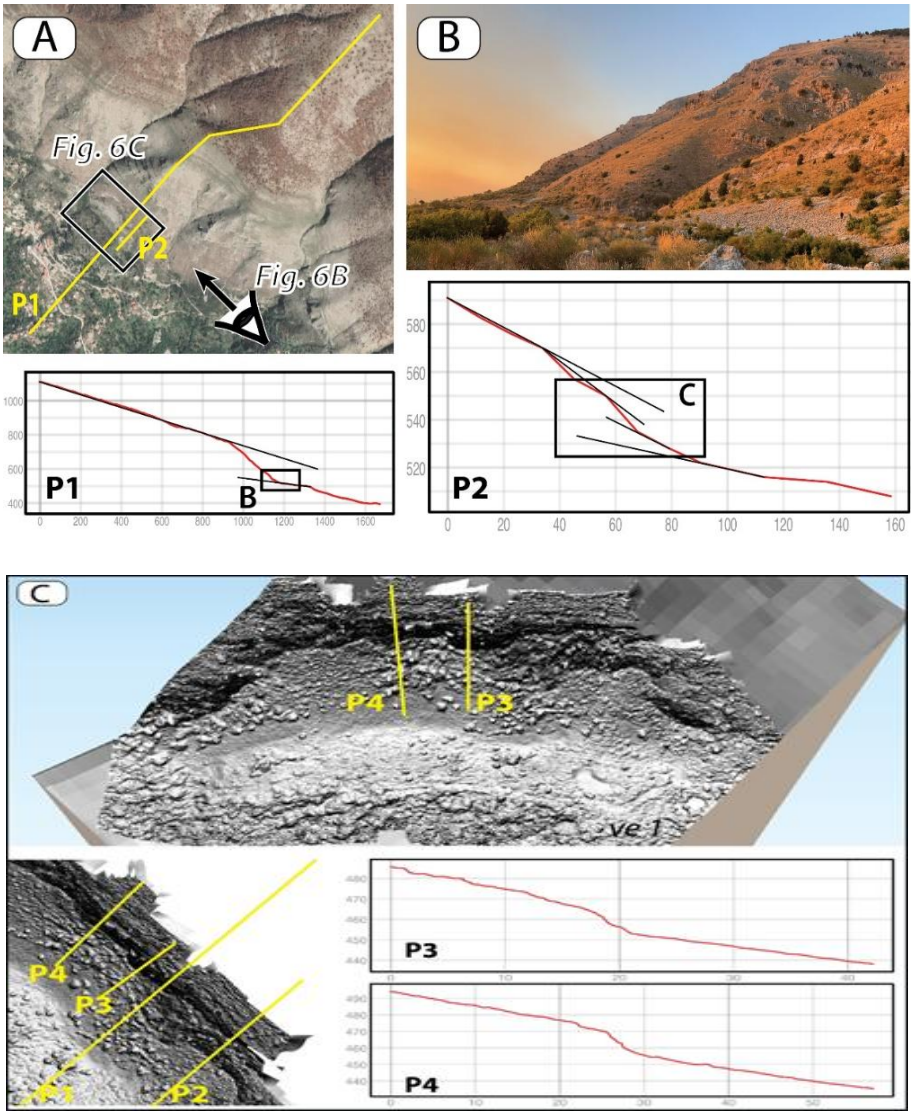

Fig. 6: (**a**) Mountain front profile, vertical height of the faceted spurs. (**b**) Vertical offset of the long-term cumulative scarp at the base of faceted spurs. (**c**) Topographic profiles across the scarp of the seismic rupture of the 1897 earthquake, DTM from drone photogrammetry. Fault plane, oriented N150, dipping 70° toward the southeast.

The concave geometry of the fault plane (Figs 5E and 6C) indicates a significant contribution of gravitational processes to the evolution of the thrust front. At the surface, we observe coseismic normal faulting, despite the broader structural and morphotectonic evidence indicating an active thrust front. This apparent inconsistency can be explained by the effect of thrust-front collapse (Pace *et al*. 2017, and the references therein), a process documented at several locations in Albania, including the Bureto thrust front (Fig. 7).

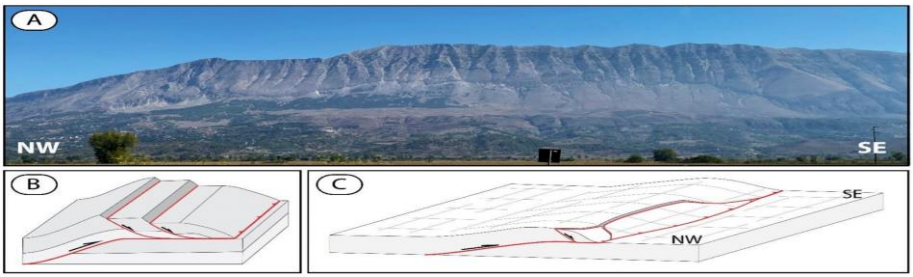

Fig. 7: (**a**) Gjirokastra valley, western slope of Mt. Bureto thrust ridge (1763 m). The fault trace is clearly visible. This fold and thrust ridge, extending until Berat, is a major structure, the first one to the northeast of the southern frontal thrust system (Fig. 4E). (**b**) Theoretical schematization of the thrust front collapse as it may have happened at Dhiveri (redrawn after Pace *et al*. 2017). (**c**) Sketch of the same mechanism along the Mt. Bureto thrust ridge of Fig. 7A.

3.2. Eastern province: the Peshkopia-Bilishti strike-slip system (1894-1942)

The tectonic extension observed in the eastern seismotectonic province is unlikely to reflect a regional extensional regime. Instead, it is interpreted as the result of localized deformation associated with pull-apart structures developed along the Peshkopia-Bilishti strike-slip fault system (Fig. 8A). This configuration is evident north of Peshkopia, where the fault bends to an approximately N-S orientation, and is particularly well expressed in the Ohrid Lake graben, which developed as a pull-apart basin along the right-lateral structure.

A destructive seismic sequence affected this fault system over a five-year period, with major earthquakes occurring on 28 September, 1896, (Mw 6.2) and 18 February, 1911, (Mw6.6-6.80), in the Ohrid pull-apart graben system (Hoffman *et al*. 2010; 2012; D'Agostino *et al*. 2022). A

longer seismic sequence spanning the period 1894-1942 may reflect the progressive activation of the entire strike-slip system.

The effects of the right-lateral displacement along the transcurrent fault system are expressed by the offset of geomorphological and tectonic features. These include the dextral offset of Mt. Deja-Mt. Kreshta massif, west of Peshkopia, which is consistent with the stress field inferred from earthquake focal mechanisms in the area (Fig. 8B). The outlet of the smaller of Prespa Lakes also shows right-lateral offset (Fig. 8C), and a comparable horizontal displacement is observed at the western termination of the Inoi fault near Lake Kastoria (Fig. 8D). In several locations, the fault plane is exposed at the surface (Fig. 9), where slickensides further confirm the right-lateral component of slip inferred from the morphotectonic analysis.

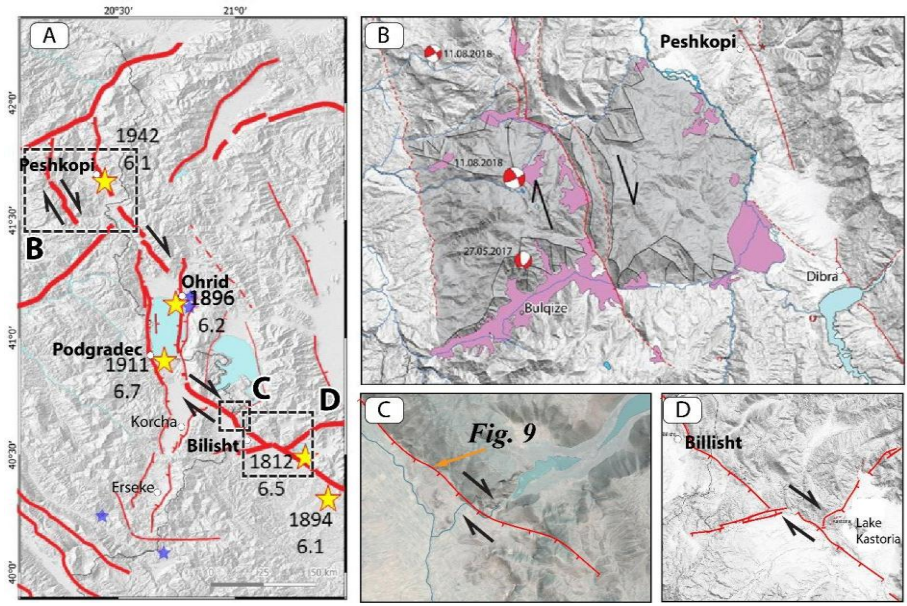

Fig. 8: Eastern province. (**a**) Erkese-Korçë-Ohrid graben and Peshkopia-Bilishti strike-slip system. Blue stars indicate hydrothermal springs. (**b**) Mt. Dejes-Mt. Kreshtes massif is right-laterally dislocated, coherent with focal mechanisms of local earthquakes. (**c**) Abandoned outlet of the Prespa Lake, right-laterally offset by the fault. (**d**) Inoi fault displaced by strike-slip.

Fig. 9: Bilishti fault. (**a**) View toward the NW. (**b**) Fault plane. (**c**) Slickensided fault plane.

4. CONCLUSIONS

The present study adopts an integrated tectonic approach applied to selected seismically active, fault-related zones. This approach combines the analysis of historical and instrumental seismicity with documentation of earthquake effects derived from contemporary reports and eyewitness accounts, together with structural and morphotectonic analyses conducted using remote sensing data and targeted field surveys at key sites. Preliminary interpretations of fault kinematics and geometry are evaluated in relation to the regional stress field and the spatial distribution of historical earthquake effects. In several areas, available geochronological data and coseismic indicators support the occurrence of recent surface faulting. Where possible, correlations are proposed between individual

fault segments and specific seismic events documented in the historical catalogue.

The overarching goal is to propose a methodology that can be progressively extended to the national scale, and refined at the level of individual fault systems. Although the examples presented here are spatially limited, they demonstrate the potential of active fault mapping as a fundamental tool for constraining seismic source models. They also highlight the importance of a multidisciplinary framework integrating geology, paleoseismology, historical seismology, and geodesy.

This contribution is intended to support a shared framework for seismotectonic mapping in Albania. By illustrating how individual fault zones can be systematically analysed and linked to seismic observations, this study provides a reference for ongoing efforts to improve the national-scale characterization of seismic sources, an essential requirement for robust seismic hazard assessment, risk mitigation and land-use planning. The preliminary nature of the case studies reflects both the richness of the available datasets and the remaining gaps in knowledge that must be addressed through future targeted investigations.

The identification and characterization of seismic sources, particular those affecting major urban centres, represent a critical priority for Albania. Cities such as Vlora are exposed to high seismic hazard, and rapid urban expansion over the past century has significantly increased the associated risk. Comprehensive mapping of active faults, improved understanding of the architecture and interconnections of fault systems, paleoseismological characterization of major structures, and continued refinement of historical and instrumental seismic catalogues, are all essential steps toward a more complete understanding of earthquake behaviour in Albania.

Advances in these areas are crucial for the development of effective seismic risk mitigation strategies, ultimately reducing the potential impact of earthquakes on communities, infrastructure, and the environment in one of the most seismically active regions of the Mediterranean.

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INTEGRATED SUBSURFACE MODELING AND LIQUEFACTION ASSESSMENT OF THE DURRËS COASTAL AREA USING CPTU AND ACTIVE SEISMIC METHODS IN SUPPORT OF CIVIL EMERGENCY PLANNING

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ABSTRACT

This study highlights the critical role of integrated geological-engineering, geotechnical, and geophysical investigations in the reliable assessment of soil liquefaction hazard. Major urban areas in Albania, many of which are located near highly active tectonic structures, have experienced significant seismic activity over the last century, with earthquakes of magnitude ranging from 5.4–6.6. The earthquakes of 21 September 2019 (Mw 5.4) and 26 November 2019 (Mw 6.3) caused severe damage in the city of Durrësi and surrounding areas, with clear manifestations of soil liquefaction observed along the coastal zone during the 26 November event. The primary objective of this research was to develop a detailed integrated subsurface model to evaluate the liquefaction potential of the coastal area of Durrësi, situated within a tectonically active region capable of generating strong earthquakes. The investigation was based on an extensive dataset including 60 geological-engineering boreholes, 71 CPTu tests (Cone Penetration Testing with pore pressure measurements) and 40 MASW surveys (Multichannel Analysis of Surface Waves). The integration of these datasets enabled a robust characterization of the stratigraphy and the key geotechnical and geophysical parameters controlling liquefaction susceptibility. The results allowed for the accurate identification of liquefiable layers and their depth ranges, providing essential input for seismic risk mitigation strategies and supporting the

preparation of the Civil Emergency Plan for the city of Durrësi. The proposed integrated methodology represents a valuable framework for sustainable coastal development and for enhancing urban resilience to seismic hazards.

***Keywords*:** liquefaction phenomenon, geological-engineering model, geophysical model, civil emergency plan

1. INTRODUCTION

Albania, located in the western Balkan region, is characterized by high seismic hazard due to its complex geodynamic and tectonic setting. From a geological and seismotectonic perspective, the country represents a young and highly active territory, making it particularly vulnerable to earthquake-related hazards, including strong ground motion amplification and soil liquefaction (Skrame, 2023). The regional seismicity pattern is dominated by frequent low-magnitude earthquakes, sporadic moderate events (moment magnitude Mw 5.5–5.9), and rare but potentially destructive strong earthquakes with Mw > 6.5. The seismic activity is mostly concentrated in the upper and middle crust and is directly related to the tectonic deformation occurring along the western margin of the Adriatic indentation (Ormeni *et al*. 2025)

Seismic activity in Albania is mainly concentrated along three major seismogenic belts: (i) the Ionian–Adriatic coastal belt, extending northwest–southeast along the boundary between the European Plate and the Adria microplate; (ii) the Peshkopia–Korça (Drini) belt, trending north–south in the eastern part of the country; and (iii) the Elbasan–Dibër–Tetovo transverse belt, oriented southwest–northeast and intersecting the former two structures (Aliaj *et al*. 2010). Over the last 114 years, at least seventeen significant earthquakes with magnitudes ranging from 5.4 and 6.6 have occurred along these belts, resulting in substantial human casualties and widespread structural damage.

Among these events, the 26 November 2019 earthquake (Mw 6.3) represents one of the most damaging seismic events in Albania's recent history, causing 51 fatalities and extensive damage in the cities of Durrës, Thumanë, Tirana, Vora, Shijak, and surrounding areas. Field observations and post-earthquake investigations highlighted the significant role of local site effects, including soil amplification and widespread manifestations of soil liquefaction, particularly within the coastal deposits of Durrës (Skrame *et al*. 2020; Ormeni and Ozturk, 2024). These effects substantially

influenced the spatial distribution and severity of damage, emphasizing the need for detailed subsurface characterization in seismic-prone urban areas (Mancini *et al*. 2021).

Accurate evaluation of liquefaction susceptibility requires reliable characterization of subsurface stratigraphy and soil dynamic properties. In geotechnical earthquake engineering practice, in-situ testing methods are widely adopted to reduce uncertainty associated with soil behavior under cyclic loading. In this study, Cone Penetration Testing with pore pressure measurements (CPTu) was employed to obtain continuous profiles of cone resistance (qc), sleeve friction (fs), and pore water pressure (u2), while Multichannel Analysis of Surface Waves (MASW) was used to derive shear-wave velocity (Vs) profiles representative of small-strain soil stiffness. The combined interpretation of CPTu and MASW data allowed for a detailed delineation of subsurface stratigraphy and the identification of potentially liquefiable sand and silty sand layers, as well as the assessment of their thickness and lateral continuity.

The integration of CPTu-derived geotechnical parameters with Vs-based dynamic soil properties provides a robust framework for liquefaction hazard assessment and site response analysis. The methodological approach presented in this study contributes to improving seismic microzonation practices and supports risk-informed urban planning and engineering design. The outcomes are particularly relevant for coastal cities characterized by young, saturated deposits and high seismic exposure, offering practical implications for the development of earthquake-resilient infrastructure and mitigation strategies.

2. DATASET, SURVEYING AND MODELLING METHODOLOGIES

A three-step procedure was adopted to develop the integrated subsoil model for the coastal area of Durrësi, Albania. Each step is detailed below.

The first step involved the construction of an engineering–geological model at the municipal scale, primarily based on the interpretation and correlation of existing borehole data and geophysical investigations (Konomi, 1980). Geological formations were interpreted in terms of lithofacies according to their sedimentological characteristics and subsequently characterized by their main physical and mechanical properties. This process allowed the definition of a representative lithotype

scheme suitable for engineering and seismic applications (Skrame *et al*. 2023).

The second step focused on data acquisition and analysis. In addition to the collection and review of results from previous studies, several new investigations were conducted. These included detailed geological, hydrogeological, and geomorphological surveys at a scale of 1:5000, aimed at updating and refining the geological map of the city. To improve the assessment of local seismic hazard and to characterize the dynamic properties of the identified lithotypes, a series of active seismic surveys was performed. A total of 40 MASW (Multichannel Analysis of Surface Waves) surveys were carried out to derive shear-wave velocity (Vs) profiles, generally reaching a maximum investigation depth of approximately 30 m. The MASW surveys were conducted using a 24-channel seismograph equipped with 4.5 Hz vertical geophones (figure 1). A receiver spacing of 2 m was selected following a preliminary evaluation of subsurface conditions, and a 10 kg sledgehammer was used as the seismic energy source. In parallel, 71 Cone Penetration Tests with pore pressure measurements (CPTu) were performed using a 20-ton piezocone penetrometer (Figure 1). Data acquisition was carried out using dedicated CPTu software. The CPTu system consisted of a hydraulic pushing and leveling unit, 1 m-long segmented rods, piezocone sensors, and a data acquisition unit mounted on the rig. The piezocone was equipped to continuously measure penetration depth, cone resistance, sleeve friction, pore water pressure, and inclination at 1 cm intervals. The cone had a projected area of 10 cm^2, and the system was capable of reaching a maximum depth of 40 m at a constant penetration rate of 2 cm/s (Figure 1).

The third step involved numerical modeling and data interpretation. To define the spatial distribution of the sedimentary infill, an integrated subsoil model was developed by combining geological, geotechnical, and geophysical datasets. The resulting model was subsequently validated and refined using geotechnical information obtained from 60 boreholes, thereby ensuring consistency between stratigraphic interpretation and measured soil properties.

Fig. 1: Geotechnical and Geophysical onsite measurements,

3. RESULTS AND DISCUSSIONS

The city of Durrës has long been exposed to significant seismic hazard and has suffered severe damage from a series of destructive earthquakes. Based on historical seismicity and the regional geological–tectonic framework, Durrësi is located close to the frontal zone of the Albanian Orogen, where compressional tectonic mechanisms dominate. These tectonic processes have generated numerous strong earthquakes with magnitudes exceeding 5.0 and macroseismic intensities reaching IX on the MSK-64 scale (Ormeni and Ozturk 2024). During the period from September 2019 to January 2020 alone, eight earthquakes with magnitudes greater than 5.0 were recorded. The most destructive event occurred on 26 November 2019 (Mw 6.4, I_0 = IX MSK-64), resulting in 51 fatalities and extensive damage to thousands of buildings in the cities of Durrës, Tirana, Kavaja, Shijak, Thumanë, and surrounding areas (Skrame *et al.* 2020).

Durrësi is located along the Adriatic coast in central Albania, within the lowland of the Periadriatic Depression. Aliaj *et al.* (2010) stated that this depression corresponds to a wide, actively subsiding foredeep basin developed at the outer front of the west-verging Albanides orogenic belt, comprising the Ionian and Kruja zones with a predominant N–S structural trend. The foredeep basin is filled with more than 2 km of marine to continental deposits, which have been affected by syn-sedimentary tectonic activity since the Pliocene. Compressive tectonics have significantly shaped the local geomorphology, leading to the formation of the Durrës Hill, which consists of Messinian to Lower Pliocene shallow-marine sandstones, conglomerates, and clays with gypsum. These formations are unconformably overlain by Quaternary deposits composed

of alluvial, lagoonal–marshy, and marine sediments, characterized by alternating layers of silts, peats, clays, sands, and gravels.

CPTu test data were used to define soil profiles, soil behavior types, and geotechnical parameters for the various subsurface layers at each investigation point. Based on mechanical characteristics such as strength, stiffness, and compressibility, as well as soil behavior type classification (SBTn), distinct soil layers were identified and characterized at each CPTu location. The interpretation of static cone penetration test results allowed for a detailed classification of subsurface strata and the derivation of their physical and mechanical parameters. The complete set of geotechnical parameters is summarized in representative stratigraphic columns, as shown in Figure 2 (Skrame *et al.* 2025).

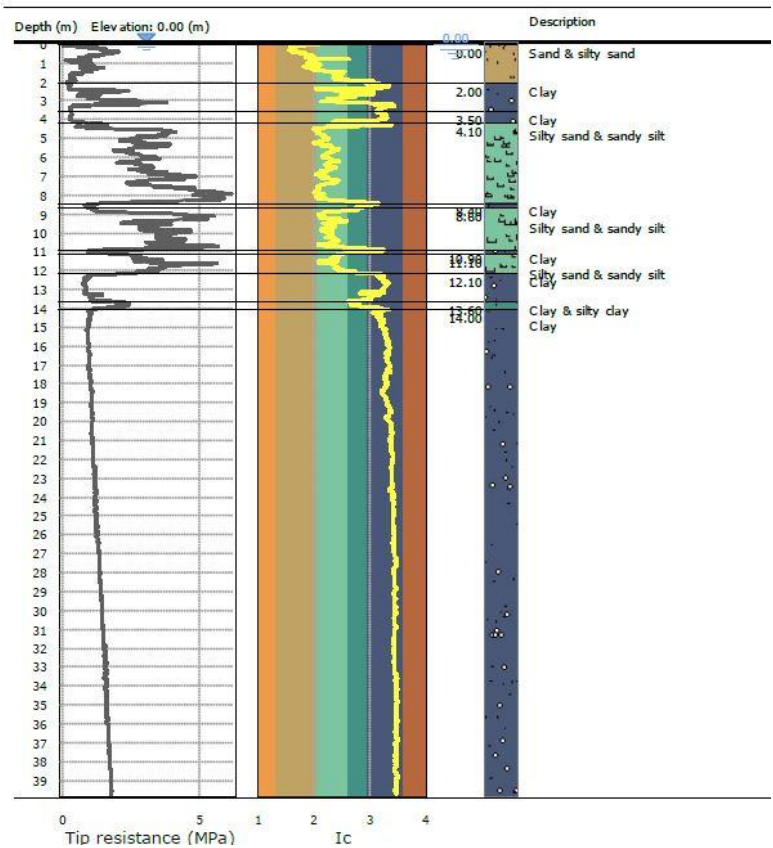

Fig. 2: Stratigraphic column type of the Durres coastal area (Skrame *et al*. 2025).

Liquefaction analyses were performed using the Robertson and Wride (1998) method. Calculations were conducted using specialized computational software. Safety factor profiles, determined in accordance with the NCEER-97-0022 procedure, indicate that liquefaction is expected to occur within the investigated area. Safety factor values lower than 1.0 (FS < 1.0) identify soil layers susceptible to liquefaction. As shown in Figure 3, liquefaction is expected primarily in near-surface layers, extending to depths of approximately 20 m. The liquefaction potential was quantified using the Liquefaction Potential Index (LPI), which ranges from 0 to 20. Values between 0 and 5 indicate low liquefaction potential, values between 5 and 15 indicate high potential, and values greater than 15 indicate very high or certain liquefaction occurrence. For the analysis, a design earthquake with moment magnitude Mw = 6.6 and a peak ground acceleration a_{max} = 0.26 g was adopted, representing the maximum horizontal acceleration expected at the seismic bedrock based on available literature data for the study area.

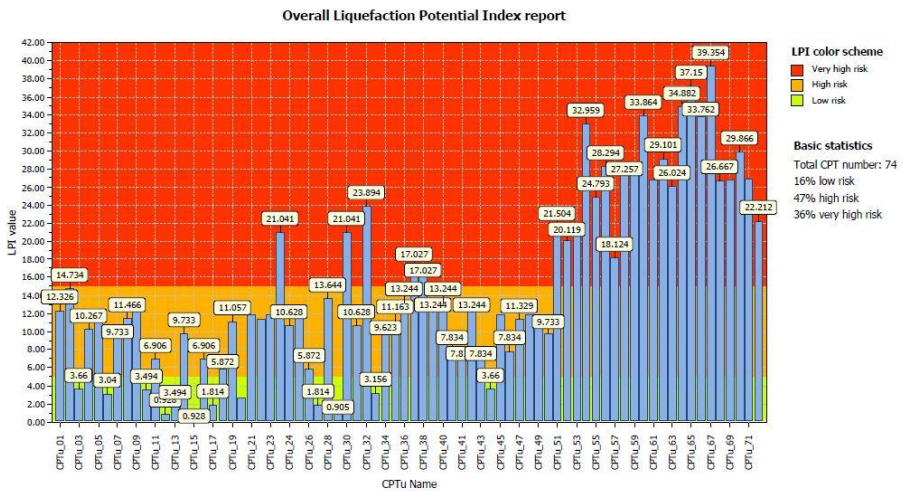

Fig. 3: Shows the presence of the Liquefaction phenomena in all the CPTu tests. Liquefaction Potential Index (LPI) shows always values above 15 for all the methodologies.

4. CONCLUSIONS

This study demonstrates that the development of an integrated subsoil model based on the combined application of Cone Penetration Testing with

pore pressure measurements (CPTu) and Multichannel Analysis of Surface Waves (MASW) constitutes a reliable and effective approach for characterizing complex coastal deposits. The implementation of this methodology in the coastal area of Durrësi, Albania, enabled detailed reconstruction of subsurface stratigraphy and the identification of the thickness and spatial distribution of sand, silt, clay, and peat layers.

The integration of CPTu-derived geotechnical parameters with shear-wave velocity (Vs) profiles obtained from MASW significantly reduced uncertainties in the estimation of soil physical, mechanical, and dynamic properties. These results provided a robust basis for evaluating liquefaction susceptibility and identifying depth intervals with a high potential for liquefaction under strong seismic loading.

The results here reported confirm that the combined CPTu–MASW approach offers substantial advantages over conventional investigation techniques, particularly in urban coastal areas characterized by young, saturated sediments and high seismic exposure. The proposed integrated methodology provides essential input for liquefaction hazard assessment, seismic microzonation, and risk-informed urban planning. Furthermore, it represents a valuable tool for the design of earthquake-resilient infrastructure and the development of effective mitigation strategies.

Declarations

Data accessibility (websites, platforms): None

Declaration of AI use: There has been no use of AI when writing the actual paper.

Author Contributions

KS – Conceptualization, compilation and preparation of the manuscript. Geotechnical and geophysical investigations. Geotechnical modeling. Geophysical modelling. Writing the original draft preparation, and writing – review & editing. **RrO** - Existing Data collection. Preparation of the earthquake catalog. Tectonic interpretation; Writing the original draft preparation, and writing – review and editing.

Authors' approval: All the authors have approved the final version of the manuscript

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COMPREHENSIVE SEISMIC RISK ASSESSMENT OF UNIVERSITY, MOTHER TERESA, SKOPJE, REPUBLIC OF NORTH MACEDONIA

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ABSTRACT

This work presents a comprehensive investigation of the seismic risk at the site of University, Mother Teresa, Skopje, Republic of North Macedonia. The study applies contemporary earthquake engineering methodologies, including geophysical investigations, probabilistic analyses of earthquake effects, nonlinear dynamic simulations of representative geotechnical models, and evaluation of key seismic parameters. The seismic risk assessment accounts for the significant the seismic activity of the region, driven by ongoing tectonic movements associated with early Miocene extensional processes. The Skopje epicentral zone is among the most seismically active regions of the country, with historically destructive earthquakes exceeding ML>6 in 518, 1955, and 1963 (all with intensity I_o=IX). Identified risk factors include local seismic hazards originating within Skopje Valley sources, as well as the potential influence of more distant seismogenic sources.

Keywords: seismic risk, Mother Theresa University, earthquake engineering methodologies

1. INTRODUCTION

This work incorporates several essential components related to the definition and characterization of seismicity at the site of the University, Mother Theresa, Skopje, Republic of North Macedonia (Edip *et al*. 2021). It begins with an analysis of the seismotectonic characteristics of the

region, providing the geological framework necessary for understanding the broader tectonic context (Edip *et al*. 2012). Building on this foundation, the study proceeds with a probabilistic assessment of seismic risk parameters, including calculation of maximum ground acceleration values for various return periods (Salic *et al.* 2020) . To enhance the understanding of site-specific conditions, the work presents a detailed description of the geological and geophysical characteristics of the location, derived from direct field investigations. These elements are integrated in the final section, where the influence of local ground conditions is analyzed, with particular attention to the amplitude and frequency characteristics of possible seismic motions (Woessner *et al.* 2015).

In conclusion, the study provides a detailed specification of seismic design parameters for different earthquakes design levels, along with final findings and recommendations relevant to the structural design of university facilities. Thorough assessment of seismic risk remains essential for ensuring safe and resilient construction.

2. REGIONAL SEISMOGEOLOGICAL CHARACTERISTICS

Over its long geological history, the territory of present-day North Macedonia and the wider region has undergone polyphase tectonic processes, sedimentation and magmatic-metamorphic processes, resulting in the formation of six fundamental geotectonic units: (i) the Vardar Zone, (ii) the Pelagonian Massif or Pelagonian Horst-Anticlinorium, (iii) the Western Macedonian Zone, (iv) the Cukali-Krasta Zone, (v) the Serbo-Macedonian Massif and (vi) the Kraishte Zone. The narrowly defined area of Çair Municipality lies within the transitional boundary between the Vardar Zone and the Pelagonian Horst-Anticlinorium. The Vardar Zone, located between the Serbo-Macedonian Massif to the east and the Pelagonian Horst-Anticlinorium to the west, originated as a Paleozoic geotectonic unit during the early Paleozoic. In the Jurassic, however, it evolved into a rift system characterized by the development of an oceanic-type of crust. Today, this geotectonic unit is regarded as the most tectonically active structure in the paraneotectonic period. According to geological maps, the study site is positioned within a belt of Miocene sands, clays and marls, as well as middle river terraces from the Pleistocene age. A clearly defined fault is mapped to the south of the location, extending westward for more than 10 km along mount Vodno in Skopje.

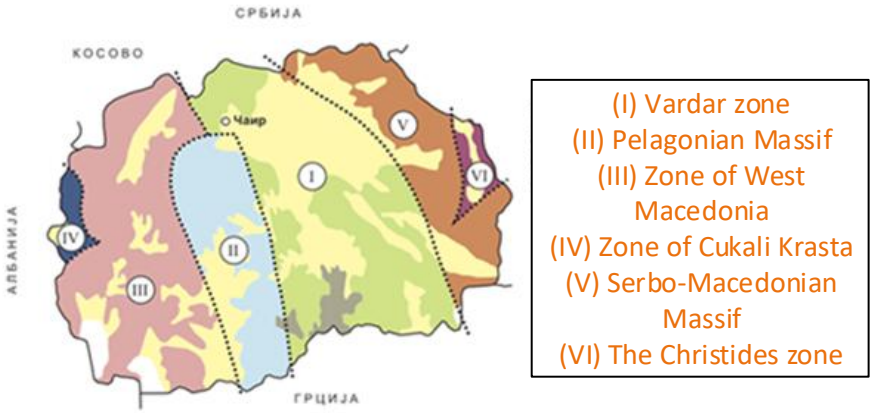

Fig.1: Schematic representation of the main geotectonic units in North Macedonia

The Vardar Zone, located between the Serbo-Macedonian Massif to the east and the Pelagonian Horst-Anticlinorium to the west, originated in the early Paleozoic but was transformed during the Jurassic into a rift system characterized by the development of an oceanic-type crustal crust. Today, it is regarded as the most tectonically active structure in the para-neotectonic period, comprising tectonic blocks ranging in age from the Proterozoic to Quaternary. The Pelagonian Horst-Anticlinorium represents a central massif composed of high-grade Proterozoic metamorphic complexes, bordered by marginal belts of low-grade Riphean-Cambrian metamorphic rocks. The core of the massif consists of gneiss-mica schist assemblages and amphibolites, overlain by mixed sequences of gneisses, mica schists and thick beds of Proterozoic marbles in the upper structural levels. The Skopje epicentral area is widely recognized as one of the most seismically active areas in the Republic of North Macedonia. Historical records document several strong earthquakes with ML>6, notably the events of AD 518 (ML=6.05, MW=6.08, I0=IX), 1955 (ML=6.05, MW=6.08, I0=IX) and 1963 (ML=6.1, MW=6.13, I0=IX), (Figure 2).

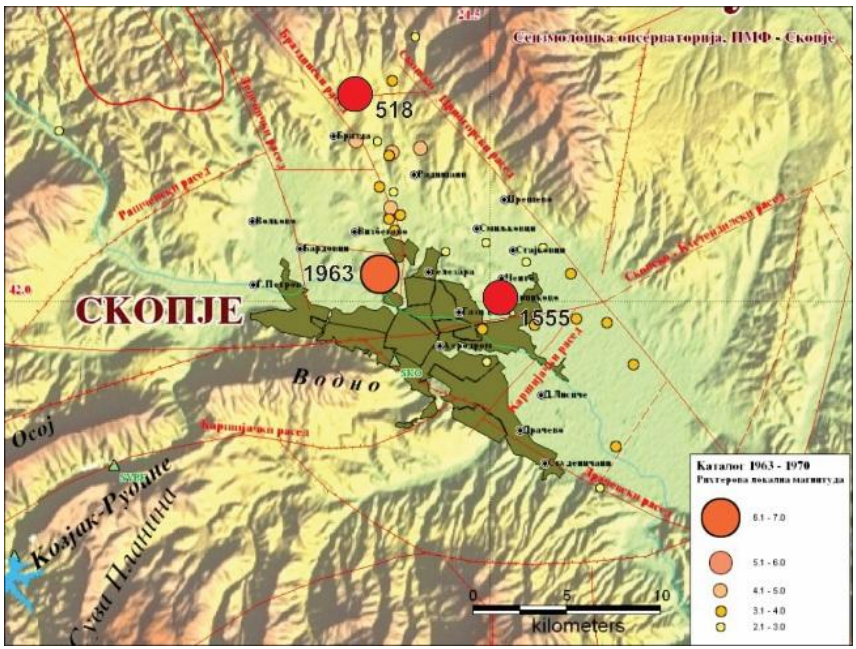

Fig.2: Epicentral map of historical earthquakes (518 and 1555) and earthquakes from the territory of the Skopje epicentral area occurring in the period 1963 – 1970. (Data source: Seismological Observatory at UKIM-PMF, Skopje).

3. SEISMIC HAZARD

In determining the seismic hazard for the planned location of Mother Teresa University in Skopje, the most-up-to-date knowledge of the region's the seismotectonic characteristics of the region's seismotectonic characteristics has been incorporated, with particular emphasis on the geological and tectonic framework, neotectonic features, seismogenic zones, and the latest available seismological data. The seismic hazard at the site was assessed using the probabilistic seismic hazard assessment (PSHA) method, which is based on the spatial and typological characterization of seismic zones, where seismicity is assumed to follow Poisson distribution. Two different mathematical models of seismic hazard were applied. The results are presented cumulatively for several return periods of interest (50, 100, 200, 500 and 1000 years), calculated for ground type A according to Euro Code (EC) classification, and expressed as peak ground acceleration (PGA) in units of gravitational acceleration.

Table 1 provides the expected average maximum acceleration on bedrock (PGA) for return periods of seismic action of 50, 100, 200, 500 and 1000 years.

Table 1. Expected average maximum accelerations on bedrock PGA

Return period in **years**	50	100	200	500	1000
Acceleration in **g**	0.114	0.153	0.201	0.283	0.335

4. SEISMO GEOLOGICAL INVESTIGATIONS

The geophysical investigations within the framework of this work were conducted with the purpose of determining the parameters of the lithological environments of the investigated location, which have local influence on the changes of regional seismic force.

Fig.3: Investigated location

The geophysical investigations conducted in this study aimed to dertermine the lithological parameters of the site, which exert a local influence on variations in regional seismic forces results of the

investigations are presented as 2D seismic sections that clearly illustrate both vertical and lateral variations in seismic wave velocities. According to existing engineering-geological data, the broader Skopje area is composed of alluvial-proluvial sediments (gravel, sand, and clay) and Mio-Pliocene sediments consisting of gravel, sand, clay, marl, marlstone, and conglomerates. The Neogene sediments and Quaternary deposits on the surface that form the Skopje Depression attain a maximum thickness of approximately 2500 meters, underlain by older Paleozoic crystalline rocks, quartzites and marbles. At the study site, existing geological information indicates that the surface layers consist of sandy clayey silt, clay, and marly silt, underlain by more compact Mio-Pliocene sediments, including dense clay, marls, sands, and marlstone. The geophysical investigations enabled the delineation of subsurface layers based on contrasts in seismic wave propagation velocities (Bojadjieva *et al*. 2022).

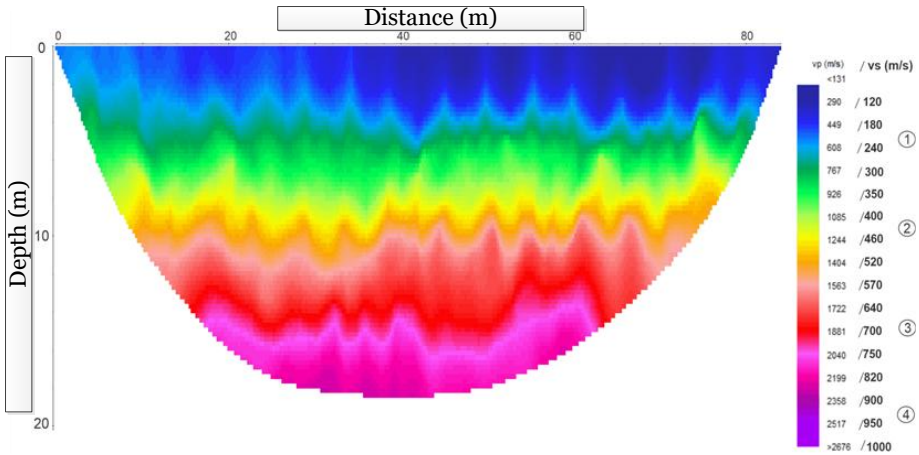

Fig.4: Seismic refraction profile.

5. EFFECTS OF LOCAL SOIL PARAMETERS

The local geotechnical environment has a significant influence on the characteristics of ground- surface motion during earthquakes. This influence is manifested through modifications in the amplitude-frequency characteristics of surface ground motion relative to the corresponding seismic excitation at bedrock level. For the purpose of mathematical analyses of local ground effects, the geological environment at the site is

represented by an appropriate mathematical model. This model incorporates, both qualitatively and quantitatively, the key mechanical parameters of the near-surface geological layers that predominantly control the modification of seismic amplitude and frequency. Based on the results of the geophysical and geotechnical investigations, the mathematical model-M1 for the site has been defined, as presented in Figure 5 (Bojadjieva *et al*. 2022).

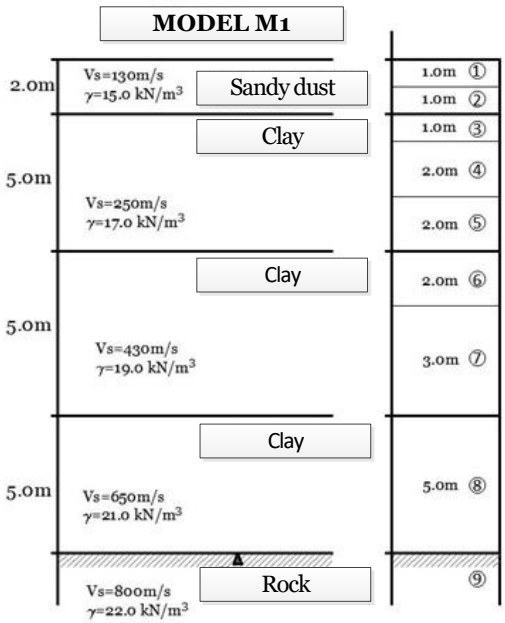

Fig.5: Matematical model of the location.

For the seismic base of the models, a transverse wave velocity of Vs≥800m/s has been adopted (Bojadjieva *et al*. 2022). As input excitations for the analyses, recorded earthquake acceleration time histories were used, selected to be critical with respect to the dominant periods of the location. The following accelerograms were employed: ACC1 - El Centro N-S, USA, 1940, (M=6.7), selected as a representative excitation for earthquakes from nearby sources with magnitudes in the range M=6.5-7.0. ACC2- Robič N-S, recorded during the earthquake in Friuli, Italy, on 15.09.1976 (M=6.1), chosen as an impulsive excitation representative of a strong local event. ACC3 -Ulcinj-Albatros N-S, recorded on rock during the Montenegro earthquake of 15.04.1979 (M=7.0). ACC4-Bitola N-S,

recorded on 01.09.1994 (M=5.2-5.4). ACC5 -Ulcinj-Olympic N-S, recorded on soil during the Montenegro earthquake of 15.04.1979 (M=7.0), selected as a representative excitation of a large-magnitude earthquake with a relatively broad frequency band of maximum amplitudes.

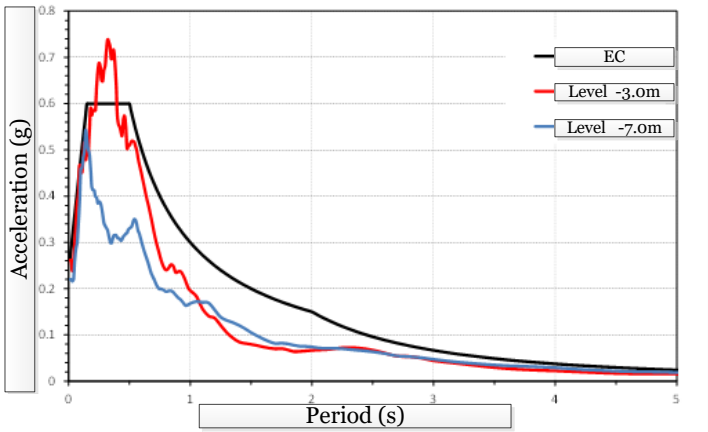

Fig.6: Average acceleration spectra for different depths for 5% damping at assumed foundation levels compared with the Eurocode acceleration spectrum

The seismic design parameters of the structure were determined based on the results of the conducted investigations. Considering the requirements of dynamic analysis and design of structures, the seismic parameters are presented as expected maximum accelerations and acceleration time histories. The determination was been carried out by incorporating the probabilistic seismic hazard of the location—reflecting its seismotectonic hazard methodology that integrates technical methodology that integrates technical, economic, and technological considerations. This comprehensive approach provides an accurate assessment of seismic threat and ensures that construction solutions remain both safe and economically viable. The adopted methodology accounts for all factors influencing structural performance during seismic events, including life-cycle cost considerations and the technologies available in contemporary engineering practice.

The maximum ground accelerations at the cite depend on the bedrock accelerations and on the seismic influence of the local geotechnical environment, expressed through the dynamic amplification factor (DAF). This relation demonstrates that the intensity of ground motion at the

surface results from two primary components: the initial seismic excitation generated at the source and its subsequent modification by the overlying soil layers.

Table 2. Maximum acceleration for different time periods of recurrence

Acceleration a(g)	**Return period T (years)**				
	50	100	200	500	1000
Acceleration in rock	0.114	0.153	0.201	0.283	0.335
Level of foundation (-3.0m)	0.171	0.2295	0.3015	0.4245	0.5025
Level of foundation (-7.0m)	0.12768	0.1714	0.2251	0.317	0.3752

The expected accelerations to which building structures may be exposed are defined by seismic hazard parameters, which refer to longer time periods significantly longer than the service life of the structures themselves. This arises the practical question of selecting the occurrence period of a period of earthquakes of a given intensity that should be considered for defining seismic design parameters. The first step in determining seismic risk is the assessment of seismic hazard. The subsequent step incorporates additional parameters of fundamental importance—such as the acceptable level of seismic risk and the service life of structures — into the seismic risk model, using a binominal probability distribution.

For different combinations of structural service life and acceptable seismic risk, corresponding return periods are obtained. The relationship among these variables is presented graphically in the diagrams shown in Figure 7. These diagrams are spatially independent and may be applied to any location within seismic zone, provided that the return-period curves of maximum accelerations for the specific site have been previously determined.

Using these diagrams, seismic design parameters — specifically maximum accelerations — can be defined to match the structures's service life and acceptable risk level. In other words, seismic acceleration can be determined as a function of return period and the probability that the design

parameters will not be exceeded during the structure's operational life. The considerations of rationality and risk in seismic design require the application of two criteria:

- **Design earthquake.** Structural analysis is performed for a moderate-intensity earthquake that has a high probability of occurring at least once during the service life. The allowable level of damage is such that it can be anticipated, controlled during design, and repaired relatively easily.
- **Maximum earthquake.** Structural analysis is performed for a strong earthquake that has a low probability of occurring during the structure's service life (Semblat *et al.* 2005).

The fundamental parameters for seismic design—and the maximum accelerations—were determined through seismic hazard and seismic risk analyses using the following assumptions:

- service life of the structure is 100 years and more
- for the design earthquake, the acceptable level of seismic risk is 30-40%
- for the maximum earthquake, the acceptable level of seismic risk is 10-20%

By applying these assumptions together with the functional relationships between maximum surface accelerations and their recurrence periods (Figure 7a), and between structural service life, risk level, and return period (Figure 7b), the corresponding acceleration values for both the design earthquake and the maximum earthquake have been derived. These values form the basis for safe and reliable seismic design, ensuring an appropriate balance between structural safety, the probability of occurrence of earthquakes of different intensities, and the economic considerations associated with implementing protective measures.

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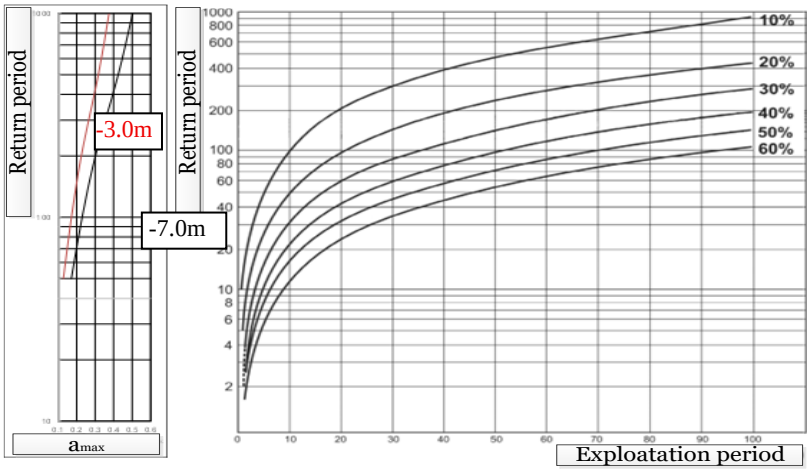

Fig.7: a) Maximum acceleration at foundation level for different return periods b) Relationship between service life of structures, risk level and earthquake return period spectra for different depths for 5% damping at assumed foundation levels.

Based on the comprehensive study conducted for the assessment of local seismic risk and the analysis of dynamic ground response, several important conclusions have been reached that define the fundamental parameters for the seismic design of the planned structure. The analyses clearly demonstrate that the dominant periods of the site represent a key characteristic for understanding the dynamic behaviour of the ground during seismic events. This information is essential for designers, as it indicates how the soil will respond at specific frequencies and allows them to implement appropriate measures to avoid harmful resonance between the structure and the ground.

The results of the site-specific seismic response analysis reveal a critical aspect of local ground behaviour: amplification effects within the surface layers are highly pronounced and significantly influence the intensity of seismic motion. At the planned foundation depth of –3.0 m, the dynamic amplification factor (DAF) reaches 1.5, indicating a 50% increase in seismic motion compared to bedrock. This considerable amplification is attributable to the specific mechanical properties of the near-surface layers and highlights the need for special design measures. In contrast, at the deeper foundation level of –7.0 m, the amplification factor is 1.12, corresponding to a more moderate 12% increase, suggesting that deeper foundations offer more favourable seismic conditions.

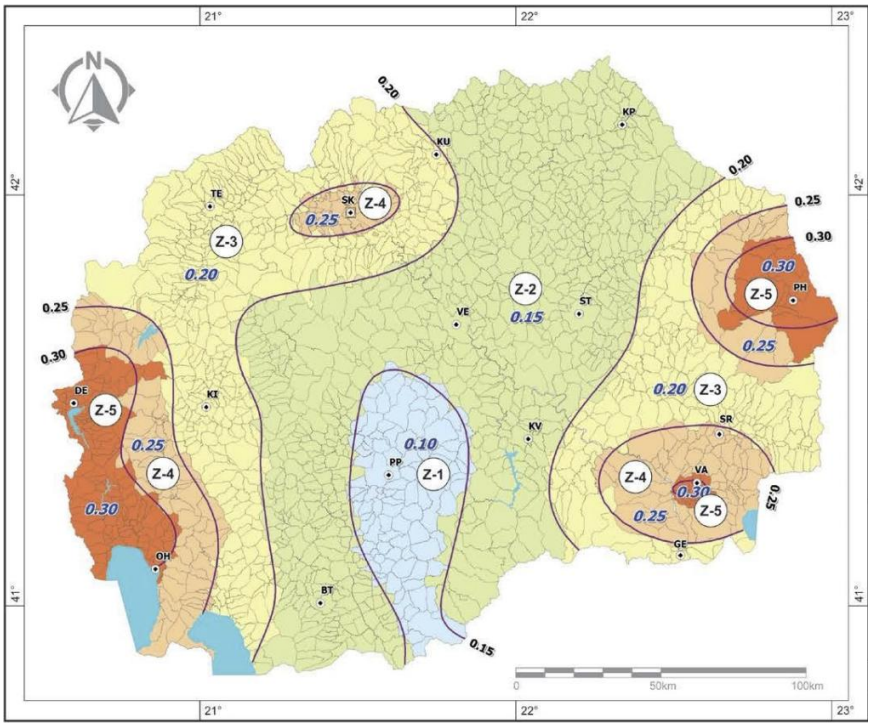

Fig.8: Map of seismic zoning for values of peak ground acceleration scaled with gravity **g** (Standardization Institute of the Republic of North Macedonia (2020) Eurocode 8: Design of Structures for Earthquake Resistance. Part 5: Foundations, retaining structures and geotechnical aspects – National annex. Reference number: MKC EN 1998-1:2012/HA:2020)

These higher acceleration values define the structural safety limits for the most severe credible seismic events, ensuring that the structure will retain its integrity even under the most critical loading conditions. The results are in line with findings from comparable site response studies conducted in similar geological environments across the Balkan region, where amplification factors between 1.4 and 1.6 are commonly reported for shallow alluvial deposits. Studies from other seismically active areas of Southern Europe—particularly Greece and Turkey—have documented comparable amplification characteristics for sites with analogous soil profiles, further validating both the methodology and the results of the present analysis (Semblat *et al*. 2005; Kanli *et al*. 2008; Pitilakis *et al*. 2012).

The adopted design strategy, which integrates site-specific ground response analysis with probabilistic seismic hazard assessment, is consistent with international best practice as recommended by current Eurocode provisions. It also aligns with methodologies successfully implemented in recent large-scale infrastructure projects across seismically active regions of Southern Europe and the broader Mediterranean basin (Tarchini *et al*. 2025).

6. CONCLUSIONS

In conclusion, the clear differences in acceleration values between the two foundation levels highlight the importance of selecting an optimal foundation depth. A deeper foundation provides significantly more favourable seismic conditions by reducing the influence of surface-layer amplification. While the numerical results offer solid guidance for design decisions, it is important to acknowledge that the amplification factors and acceleration values are subject to inherent uncertainties. These arise from variability in soil properties, limitations in defining the precise geometry of subsurface layers, and epistemic uncertainties in the ground-motion prediction models applied in the probabilistic analysis. A comprehensive sensitivity analysis addressing key input parameters—such as variations in shear-wave velocity, soil damping ratios, and the selection of seismic input motions—would enhance confidence in the robustness of the conclusions and help quantify the range of potential outcomes under different assumptions.

These findings provide a sound scientific basis for informed decision-making during the design phase and help ensure that the planned structure meets the highest standards of seismic safety in accordance with the geological and seismotectonic characteristics of the site. Nevertheless, several limitations should be recognized. The analysis relies on a one-dimensional (1D) site response model which, although suitable for horizontally stratified conditions, does not account for potential two-dimensional or three-dimensional basin effects caused by lateral geological variations or irregular bedrock topography. In addition, the equivalent-linear method used, while widely adopted in engineering practice, cannot fully capture the nonlinear soil behaviour expected under very strong ground motions.

Future work could strengthen the analysis by incorporating more detailed investigations of layer orientation and possible basin-geometry

effects through advanced geotechnical exploration and two-dimensional or three-dimensional numerical modeling. Further improvements may also include fully nonlinear site response analyses to better represent soil behaviour at high strain levels, parametric studies to assess sensitivity to key soil parameters, and the use of site-specific recorded ground motions, where available, to validate analytical predictions. Moreover, this analysis provides a useful reference framework for geophysical investigations examining the influence of different subsurface layers and can serve as a benchmark for future studies employing more advanced modeling techniques and additional site-characterization data.

Declarations

Data accessibility (websites, platforms): Information is available online: www.iziis.ukim.edu.mk

Declaration of AI use: AI use has not been practiced since there is no big amount of Data

Authors' contributions:

KE- conceptualization, writing; VSh, JB, RS-M, MS, IGj-review and editing.

Authors' approval

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

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SEISMIC ASSESSMENT OF STOCK BUILDINGS FROM THE 1960s IN KOSOVO: AN INTEGRATED ANALYTICAL AND EXPERIMENTAL APPROACH

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ABSTRACT

Buildings constructed during the 1960s constitute a substantial portion of the existing building stock in Kosovo, typically characterized by frame-type systems with infill walls, as well as mixed constructions combining masonry and cast-in-place concrete. These buildings were designed and built in a period when seismic design criteria were not systematically incorporated into building codes, rendering them particularly vulnerable to seismic risk under current usage conditions. This study develops an integrated approach for assessing seismic risk in these structures, combining in-situ testing, laboratory analysis of existing materials, and advanced numerical modeling based on nonlinear pushover analysis. Within this framework, dynamic characteristics are identified through ambient vibration testing, and structural capacity is compared with seismic demand in accordance with Eurocode 8. To synthetically represent structural performance and risk, the Vulnerability Index (VI) is used as an analytical indicator, enabling cross-typology comparisons and helping prioritize intervention strategies. To reduce risk and enhance both load-bearing capacity and ductility of existing structures, different intervention strategies are examined. Alongside conventional strengthening methods, the analysis includes proposals for new techniques and materials, emphasizing the use of Fibre Reinforced Polymers (FRP). FRP materials offer lightweight solutions with minimal impact on structural mass and architectural appearance, making them suitable even for buildings of historical or cultural significance. The application of these technologies provides a sustainable approach to modernizing the old building stock in the region, preserving functional and architectural integrity while improving seismic performance in line with contemporary engineering standards.

***Keywords*:** Masonry buildings, Seismic vulnerability, Structural behavior, FRP, Load-bearing capacity

1. INTRODUCTION

Masonry buildings constructed during the 1960s represent a significant portion of the building stock in Prishtina, sharing similar design concepts and construction characteristics. In general, architectural layouts, structural configurations, materials, and construction techniques are comparable across this building group. The main concern is the application of regulations at the time, which were limited regarding structural behavior under seismic effects, resulting in considerable damage during earthquakes in the region. Furthermore, the long-term use of these typical buildings, often without significant maintenance or intervention, has limited their service life due to the effects of aggressive environmental conditions. The seismic performance of masonry structures is closely related to material properties, the interaction between elements (e.g., clay blocks and mortar), and, in some cases, cooperation with reinforced concrete elements. This paper focuses on assessing the seismic behavior of these structures, applying analytical methods supported by prior research (analytical modeling, pushover analysis, and spectral analysis), as well as experimental methods for material characterization (both non-destructive and destructive). Using these data, the study analyzes the potential for structural improvements and enhances understanding of load-bearing capacity, with particular emphasis on strengthening using FRP materials and techniques. The analyses and evaluations also provide technical recommendations for structural reinforcement and seismic risk management.

2. FACTORS INFLUENCING THE BEHAVIOR OF UNREINFORCED STRUCTURES

The study aims to establish comparability between theoretical predictions and the observed behavior of structures during recent earthquakes, such as those in Albania (November 2019) and Croatia (March 2020). The selected buildings for analysis are masonry structures from the 1960s in Kosovo, mainly in the Ulpiana–Prishtina area, as well as similar collective residential buildings up to five stories high, constructed according to the former JUS standards. As a reference, observed damage in similar structures in Albania and Croatia—belonging to the same construction category—is used for comparison, as illustrated in Fig. 1(a, b, c).

Fig. **1**: (a) Behavior of buildings in Albania; (b) Buildings in Pristina; (c) Behavior of buildings in Croatia.

In the preliminary analyses and evaluations, several factors influencing the behavior of unreinforced structures were identified in relation to the observed damage:

- Low load-bearing capacity of masonry elements;
- Inadequate load-bearing capacity and poor quality of mortar;
- Lack of regularity in plan and low load-bearing capacity of walls;
- Design and construction errors in vertical elements;
- Errors and interventions in ground floors;
- Redistribution of space or openings in walls;
- Overall stiffness of the structure as a whole.

Interventions on ground floors are a common practice, often motivated by changes in space usage, and are frequently carried out in an uncontrolled manner. Post-earthquake case studies and observed behavior of masonry structures indicate that such interventions significantly limit structural ductility, directly reducing load-bearing capacity and the overall strength of the masonry material. The use of low-quality mortars and their improper application further reduce masonry resistance, contribute to crack formation, and decrease the shear capacity of walls.

3. SEISMIC PERFORMANCE ASSESSMENT OF STRUCTURES

Research and findings by numerous authors in the field of seismic risk assessment provide a deeper understanding of the behavior of masonry structures and reinforced concrete (RC) frames with infill walls (Dautaj *et al*. 2018a). Under seismic loading, masonry infills often sustain damage without causing immediate structural collapse; however, they may contribute to the development of soft-story mechanisms (Pauley *et al*. 1992).

The appearance of diagonal cracks enables the identification of failure modes, which, in some cases, involve the formation of plastic hinges at the connections between columns and upper floors (Fig. 2). This figure illustrates the equivalent diagonal strut model used to represent the behavior of masonry infill walls within RC frames under lateral loading.

In this model, the infill transfers most of the horizontal force along a compressed diagonal band, which is mechanically represented as a single diagonal strut with an effective width and angle. This simplified model captures the stiffening effect of the infills and their interaction with the surrounding RC frame during seismic events. A numerical modeling approach illustrating this behavior is presented in Fig. 3.

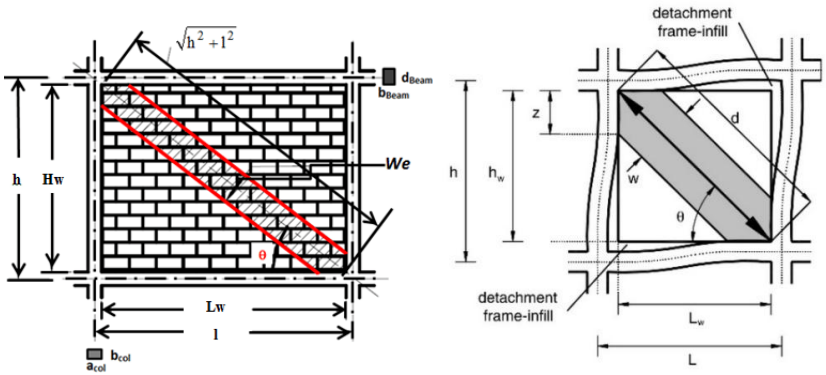


Fig. **2**: The tangential sliding model of infill masonry (Paulay and Priestly, 1992).

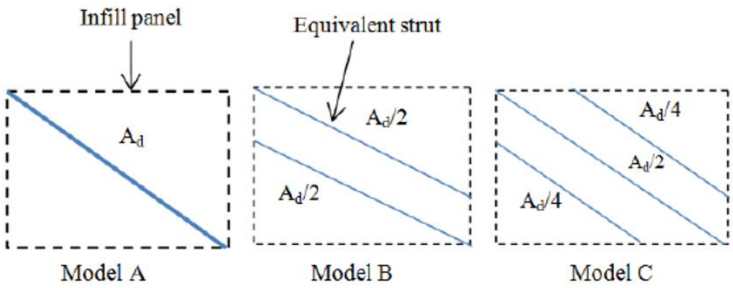


Fig. 3. Different models for the analysis of infill masonry.

In the framework of structural performance assessment and analytical calculations, it is necessary not only to evaluate relative displacements but also to determine the maximum absolute displacement that may occur at a given point in time. This enables the identification of the maximum seismic force acting on the analyzed structure. To this end, several earthquake accelerograms from different countries are considered, alongside the corresponding elastic response spectra based on the EN 1998-1 standard. Figure 4 presents a comparison between real earthquake response spectra (Beograd, Petrovac, El Centro, Ulcinj) and the elastic design spectra defined by Eurocode 8 (EC8) for different soil types (A, B, C, D), using a behavior factor q=1.0q = 1.0q=1.0, which corresponds to no reduction for ductility.

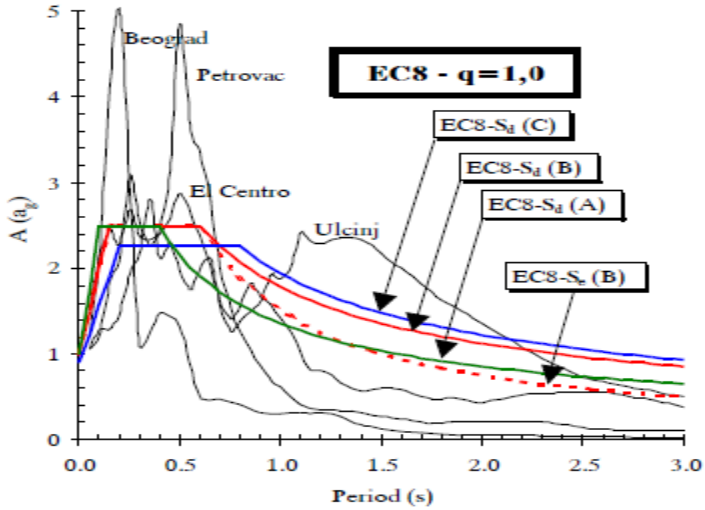


Fig. 4. Elastic acceleration spectra of earthquakes in different locations.

3.1. *Seismic Performance of Masonry Structures – General Data*

A key aspect in evaluating the seismic performance of masonry structures is the assessment of their vulnerability, which is closely influenced by a range of factors. These factors affect both the determination of the vulnerability class and the overall evaluation of seismic risk as part of a structured analysis procedure. The relevant evaluation factors are summarized in Table 1.

Table 1. *The respective factors.*

High Vulnerability	Low Vulnerability
Insufficient quality of materials (weak mortar, fragile/weak units), poor internal bonding of masonry (irregular undressed stones, multi-leaf masonry without transverse connections, etc.).	Regular and durable units, good bonding and interlocking between units; masonry behaves as a monolithic whole throughout the wall thickness.
Very thin walls (suspectible to out-of-plane instability).	Limited wall slenderness; resistance to out-of-plane failure.

Lack of effective connections between walls and between walls and horizontal structures; absence of structural redundancy.	Good interconnection at wall corners, presence of tie rods and ring beams at each floor (and roof) level to enable “box action”; effective wall–floor connections that reduce stress concentrations.
Intermediate floor systems do not act as diaphragms.	Floors sufficiently stiff and resistant to provide out-of-plane support for walls, increase structural redundancy, and allow redistribution of internal forces.
Presence of horizontal thrusts (e.g., from roofs or arched/vaulted structures) resisted only by the out-of-plane resistance of walls.	Horizontal thrusts resisted by in-plane action of strong/bracing walls or by suitable structural elements (tie rods, floor diaphragms), forming a closed equilibrium system.
Excessive unsupported floor spans, walls widely spaced and irregularly distributed.	Limited floor spans; shear walls regularly distributed in at least two orthogonal directions.
High structural and non-structural masses and low material strength.	Masses and weights produce a low compression/strength ratio.
Structural irregularities in plan (torsional effects, stress concentrations) and in elevation (inefficient load paths, stress concentrations).	Regular structure, sufficient resistance to torsion, regular load path from top to foundations.

One of the main objectives of using these factors is classify structures accoding to the data reported in the authors (Cosenza *et al*. 2004) and presented in Table 2.

Table 2. *Classification of masonry structures*

	Non-Engineered (NE)	**Engineered (E)**
Structurally Inadequate (NS)	NSNE	NSE
Structurally Adequate (SD)	SDNE	SDE

4. CASE STUDY – SEISMIC RISK ASSESSMENT

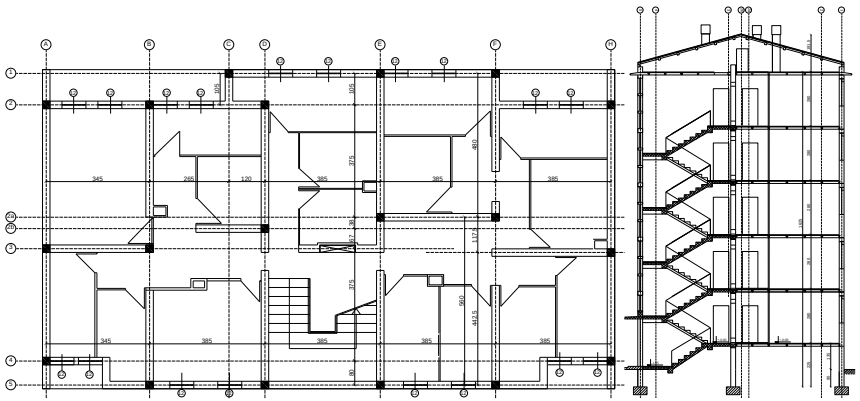


Fig. 5: *Geometry of typical floor plan.*

To evaluate the behavior of the structure, including its seismic response, several material tests and full-scale structural assessments were carried out. The building selected for this study is a six-story structure constructed in the 1960s in the Ulpiana district of Prishtina. It represents part of a complex of repetitive buildings with similar geometric and structural characteristics. The structure consists of a reinforced concrete (RC) frame with brick infill walls, built using the construction technologies of that period, including horizontal RC beams and concrete of varying quality between the lower and upper floors. With a layout of five bays in the X-direction and two in the Y-direction, the building features spans of up to 3.85 m and 5.60 m, and incorporates reinforcement with Ø16 mm and Ø14 mm steel bars in the columns of different floors. This building typology is representative of mid-20th-century construction in Kosovo, which today faces considerable challenges in meeting modern seismic design requirements. The methodology applied in this case study is summarized in Table 3.

During the Ambient Vibration Testing (AVT), a set of tri-axial accelerometers from the Digitex AVM system was installed. The sensors recorded ambient motion at a sampling rate of 200 Hz, which is adequate for identifying modal frequencies within the typical range for mid-rise masonry and RC buildings (0.5–15 Hz). Schmidt hammer testing was performed in accordance with EN 12504-2, using a Type N rebound

hammer. Before each testing session, the instrument was calibrated using a standard steel anvil as recommended by the manufacturer. Each flat jack was calibrated in the laboratory using a steel reaction frame and hydraulic pump to establish the pressure–volume curve, and a reference pressure gauge with ±0.2% accuracy was used for calibration of the pressure cell.

Table 3. Followed methodology

Chapter	Methodology	Main Results
1. Description of the Building	On-site inspection; Analysis of structural layout; Identification of key geometric and material characteristics	Six-story RC frame building with infill walls; Repetitive design in the neighborhood
2. Ambient Vibration Tests and Model Calibration	Non-destructive AVT tests with accelerometers; Processing with EFDD; Calibration with 3D numerical model	Four global modal shapes identified; Good agreement between model and tests; Effect of confined masonry clearly observed
3. Material Characterization	Schmidt hammer test for in-situ concrete; Laboratory tests for masonry bricks according to EN standards	Concrete showed higher strength than originally designed; Bricks had strength of 16–24.3 N/mm²
4. Nonlinear Static Analysis and Parametric Study	Pushover analysis with different load patterns; Parametric variations of masonry and concrete properties	Masonry increased shear capacity by 35–40%; Stronger concrete added 10–15%; Confined masonry improved calibration

4.1. *In-Situ And Laboratory Material Characterization*

To assess the actual condition of the construction materials, in-situ tests were conducted on concrete using the Schmidt Hammer method (EN 12504-2), while laboratory tests were performed on clay bricks in accordance with the relevant EN standards. The results showed that the concrete in the main structural elements demonstrated higher strength than

originally designed, indicating no significant degradation and stable mechanical properties. Compressive strength tests on masonry bricks yielded average values ranging from 16 to 24.3 N/mm², confirming considerable load-bearing capacity under seismic actions. This detailed evaluation provided a reliable basis for accurate structural modeling and for understanding the influence of masonry on the building's seismic behavior. Clay brick testing was performed in accordance with EN 772-1. The samples were prepared and analyzed, and the results are summarized in Table 4.

***Table 4.**. Brick test results.*

Sample	Force [kN]	Compressive Strength [N/mm²]	Average Compressive Strength [N/mm²]	Shape Factor [d]	Normalized Compressive Strength [N/mm²]
M1 & M2	770.5	24.3	21.3	0.75	16.0
M3 & M4	706.1	23.5			
M5 & M6	460.5	16.0			

4.2. *"Flat JACK" testing*

Flat-jack examinations were conducted on a wall at the ground-floor level to assess its mechanical characteristics as an integral component of the structure. The test results provided essential parameters for the structural analysis. An illustration of the setup is shown in Fig. 6.

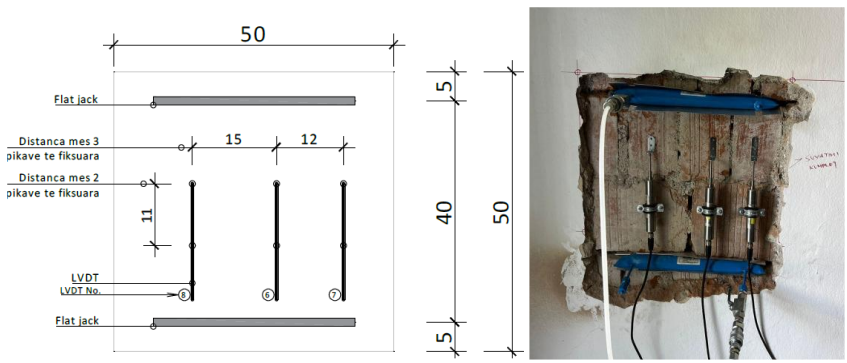


Fig. 6: Setup scheme for the positioning of the 'Flat Jack' device.

The evaluation was performed after completing the necessary preparations on the wall subjected to testing, following the scheme illustrated in Fig. 6. The results of the examinations are presented in Fig. 7, incorporating the previously calibrated measurements used for the final assessments. The graph shows the outcomes of the flat-jack test, displaying the increase in stress (MPa) in relation to the measured deformation (mm/mm) for two different instruments: the average readings from the LVDTs and Strain Gauge 6. Both data sets follow clear linear trends, indicating that the masonry exhibited elastic behavior within the applied load range.

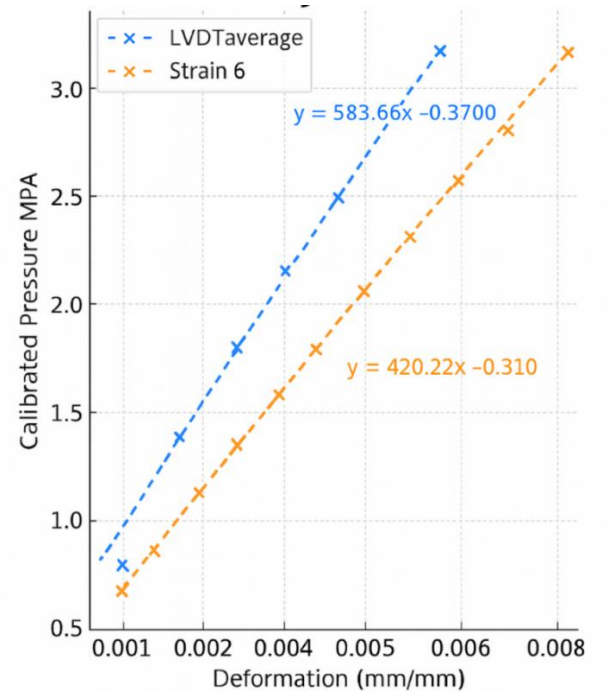


Fig. 7: The obtained results and the Pressure/Deformation ratio.

4.3.*Ambient Vibration Tests and Model Calibration*

To evaluate the dynamic behavior of the existing building, the non-destructive method of Ambient Vibration Testing (AVT) was applied. This technique enables the identification of natural frequencies, modal shapes,

and damping ratios by analyzing the structure's response to environmental excitations. Accelerometers were strategically installed on each floor, and the recorded data were processed using the Enhanced Frequency Domain Decomposition (EFDD) method. A total of eight modal shapes were identified, of which four were global modes—corresponding to movement in the X- and Y-directions and one torsional mode. These results were then used to calibrate a 3D numerical model developed using SeismoStruct and ETABS software, thereby improving the accuracy of the analyses and emphasizing the significant role of confined masonry in enhancing the structure's seismic performance. The equipment used was the Digitex AVM System, consisting of a central processing unit and multiple sensing components for data acquisition, as illustrated in Fig. 8.

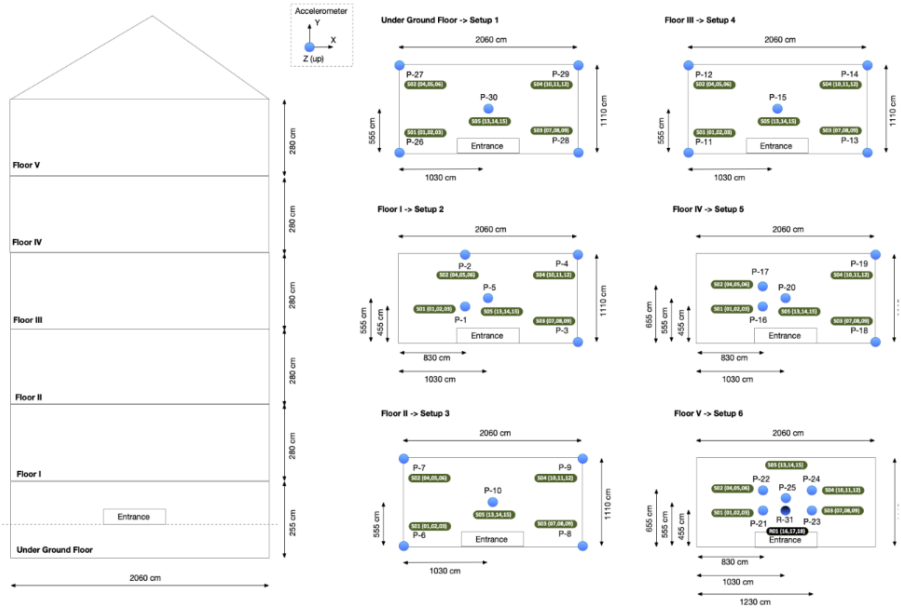


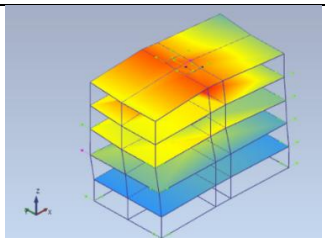
Fig. 8: Positioning positions of sensors.

The results of the analyses and the corresponding evaluations are presented in Tables 5 and 6, based on the processing performed using the FDD and EFDD methods.

Table 5. Different parameters given as results from the testing.

Mode Shape	Description	FDD f (Hz)	T (s)	EFDD f (Hz)	T (s)	ξ (%)	MAC
1	First translational mode in Y-direction + slight rotation	3.711	0.269	3.711	0.269	/	0.7453
2	First translational mode in X-direction + slight rotation	4.102	0.244	4.102	0.244	/	0.0915
3	First torsional mode in XY plane	5.518	0.181	5.518	0.181	/	0.5995
4	Second translational mode in Y-direction + slight rotation	5.762	0.174	5.762	0.174	/	0.7032
5	Local mode	6.665	0.150	6.665	0.150	/	0.150

Table 6. Testing results, core information.

Mode shape	Description	f(Hz)	T(sec)	
1	Translations in Y direction slight rotation	3.711	0.269	
2	Translations in X direction slight rotation	4.102	0.244	
3	Torsion	5.5.18	0.181	

4.4. *Nonlinear Static Analysis and Parametric Study*

To establish comparability and enable a more detailed assessment, an analytical model was developed by incorporating all relevant geometric and material parameters using SeismoBuild software. Nonlinear static

(pushover) analyses were carried out to evaluate the seismic capacity of the structure by applying incrementally increasing lateral loads. Several simulation scenarios were considered, involving variations in the mechanical properties of concrete and masonry, including the introduction of confined masonry in strategic areas such as the building perimeter and main corridors.

The results demonstrated that the addition of confined masonry and the improvement of concrete quality significantly increased the base shear capacity and reduced displacements at the defined limit states—Damage Limitation (DL), Significant Damage (SD), and Near Collapse (NC). Specifically, the use of higher-strength masonry increased capacity by up to 40%, while the application of higher-quality concrete contributed an additional 10–15%. The calibration of the capacity curves using field-test data underscores the importance of experimental validation in the seismic assessment of existing buildings and in the development of targeted strengthening strategies.

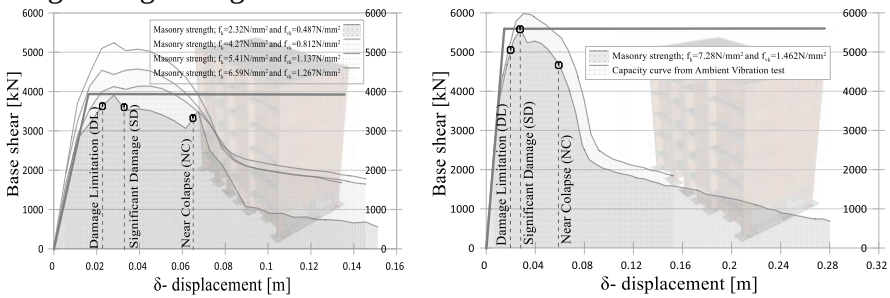


Fig. 9: Calibration of capacity curves: (a) Influence of masonry properties on structural dynamic behavior; (b) Field-test-based comparison.

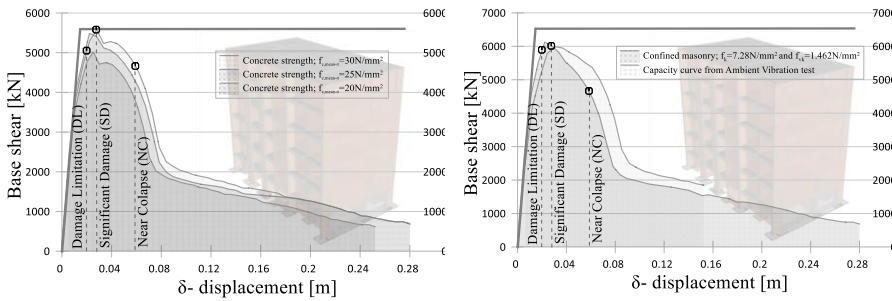


Fig. 10: Calibration process of capacity curves; (a)impact of concrete strength, (b)calibration considering confined masonry.

Figures 9 and 10 provide graphical representations that help the engineer better understand how variations in masonry and concrete properties influence the shape and behavior of capacity curves. These visual comparisons facilitate the observation of how changes in material strength, stiffness, and confinement affect the structural response, thereby enabling clearer interpretation and more accurate calibration of analytical models. Similar approaches, including investigations of the influence of infill walls on the global behavior of structures, have also been studied by Santarsiero *et al*. (2021), Martin Leal-Graciano *et al* (2020) and Moreira *et al*. (2023).

5. THE RELATIONSHIP BETWEEN SEISMIC RISK AND VULNERABILITY

Various approaches that attempt to incorporate multiple factors as an "interlinked chain" have predominantly focused on the final outputs of seismic risk, without thoroughly exploring the behavior of risk itself (Alwang *et al*. 2001). This gap exists because risk behavior is difficult to characterize and requires specific considerations for proper evaluation. A conceptual illustration of the influence of vulnerability on seismic risk is presented in Fig. 10, accompanied by explanatory notes.

5.1. *Seismic Risk and Risk Exposure*

Vulnerability begins with the notion of risk, which is characterized by the distribution of unpredictable scenarios. An example of risk categorization is provided by Alwang (2000).

Table 7. Types of Risc according the Jorgeson

Risk Category	Example of Risk
Natural risk	Floods, landslides, earthquakes, hurricanes, storms, etc.
Health risk	Epidemics, mass outbreaks
Life-cycle risk	Birth, aging, death, etc.
Social risk	Violence, terrorism, wars, etc.
Economic risk	Business bankruptcies, financial crises, etc.
Political risk	Discrimination, coups d'état, etc.
Environmental risk	Environmental pollution, land degradation, nuclear disasters, etc.

Within the framework of seismic risk assessment, the parameters required for calculating the vulnerability index are presented below. These parameters serve as key evaluation criteria for masonry structures. They are classified into three assessment levels—L (Low), M (Medium), and H (High)—and the indicative values corresponding to each category are provided in Table 7.

Table 8. Parameters for the assessment of the vulnerability index in masonry structures, categorized according to the evaluation scale: L (Low), M (Medium), and H (High).

#	Parameter	L (Low)	M (Medium)	H (High)
1	Connection between orthogonal walls	0	10	28
2	Quality of masonry	–	–	17.5
3	Connection between load-bearing walls and non-structural components	0	8.5	17
4	Spacing of load-bearing walls	0	5	9
5	Type of intermediate floor and its connection to the wall	0	4	7.5
6	Horizontal offsets of load-bearing walls	–	–	6.5
7	Regularity in plan	–	–	6
8	Type of roof and its connection to the walls	0	2	4.5
9	Vertical offsets of floors and arches	–	–	4
10	Position and interconnection of structural units as a whole	0	1	4

The Vulnerability Index (Vi) is derived from the statistical relationship between seismic intensity—evaluated from historical earthquake data—and the performance of different structural classes, combined with accumulated knowledge from typical damage assessments (Benedetti and Petrini, 1984; Marco *et al*. 2021).

5.2. *Strengthening and preventive Measures in Minimizing Seismic Risk in Masonry Structures*

Strengthening the existing building stock represents a key preventive measure for reducing earthquake-related damage, particularly in residential and public buildings. Effective and optimized strengthening interventions for existing masonry structures require a precise analysis and an accurate determination of vulnerability levels, taking into account construction typology and traditional building practices (Scupin and Vacareanu, 2023). When defining fragility parameters for various typologies—such as those analyzed through numerical models in this case study—a clear and systematic approach is necessary for selecting appropriate methodologies and materials for structural strengthening. The assessment of damage levels serves as a basis for determining spectral deformation values, which are closely connected to the probability of failure in masonry structures (see Fig. 11).

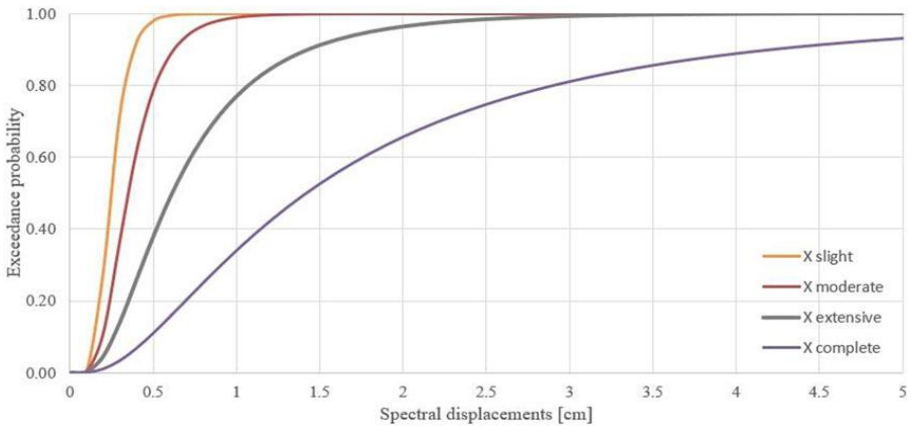


Fig. 11. Fragility curve.

The vulnerability of masonry structures necessitates several approaches and hypotheses for strengthening, with a focus on the application of contemporary methods and materials such as Fiber Reinforced Polymers (FRP) (Ahani *et al.* 2021). Existing structures often demonstrate seismic deficiencies and require strengthening at suitable and accessible locations (Sarker *et al.* 2011). Based on the model presented previously in Fig. 6, this study explores the use of FRP diagonal

reinforcement—as shown in Fig. 12—specifically the application of FRP strips functioning as tensile elements. These elements exhibit significant potential for improving the ductility of the structure and its individual components (Benedetti and Petrini, 1984; Kabashi *et al*. 2016; Moriera *et al*. 2023).

Because the flexural capacity and deformation resistance of masonry walls are inherently limited, the high tensile strength of FRP materials can effectively compensate for these deficiencies (Dautaj *et al*. 2018b).

Figure 12 illustrates the experimental setup and results for a masonry wall strengthened with X-shaped diagonal FRP reinforcement, together with the corresponding load–displacement curve obtained from cyclic testing. The images on the left show the reinforced wall configuration, while the graph on the right presents the structural response under increasing lateral displacement, including loading cycles, progressive stiffness degradation, and peak load capacity prior to softening. Together, the visual materials provide a clear understanding of the behavior of strengthened masonry under cyclic loading and the evolution of its load-bearing capacity**.**

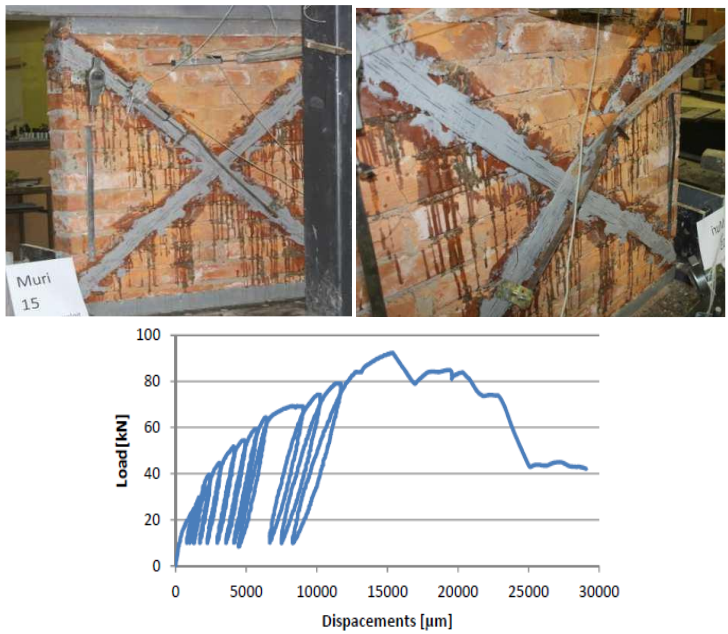


Fig. 12. a) Testing, reinforced walls. b). Displacement of the testet system.

5.3. *Cost–Benefit Analysis*

Strengthening masonry structures with FRP (Fiber Reinforced Polymer) materials offers a highly cost-effective and efficient solution for enhancing structural resistance and ductility, particularly under seismic loads. While the initial costs may be higher compared to traditional interventions, the long-term benefits and reductions in secondary impacts caused by seismic events justify the investment (Yavartanoo *et al.* 2025). The main cost–benefit aspects include:

- Lower overall cost compared with many traditional strengthening techniques
- Rapid implementation and reduced construction time
- Minimal increase in the total weight of the structure
- Ease of installation and on-site application
- Significant improvement in structural performance
- Reduction of unforeseen risk during extreme events

6. CONCLUSIONS

A considerable number of masonry structures from the 1960s were not designed in accordance with modern seismic provisions. For this reason, strengthening measures—aligned with contemporary design codes—are strongly recommended as a preventive strategy to reduce potential earthquake-induced damage (Sarker *et al.* 2011).

The building analyzed in this study forms part of a larger stock of repetitive mid-20th-century residential structures, many of which share comparable geometry, material characteristics, and construction techniques within the same neighborhood in Prishtina. Thus, this case study provides representative insights into a broader category of similar buildings. However, restricted access to a complete inventory prevents the confirmation of whether internal configurations or past interventions are consistent across the entire stock. Furthermore, while this construction pattern is not representative of the entire region, it typifies a significant portion of the capital city’s mid-century building inventory.

Regarding strengthening strategies, the application of FRP materials emerges as an effective alternative to conventional methods due to their advantageous properties, including:

- High elastic modulus (stiffness)
- High mechanical strength
- Excellent corrosion resistance

- Low weight and ease of application

Based on the analyses conducted in this study, the following main conclusions can be drawn:

- Strengthening with FRP can lead to a substantial increase in elastic stiffness, thereby reducing structural damage during seismic actions.
- GFRP (Glass Fiber Reinforced Polymer) is particularly well suited for strengthening walls with openings, especially when reinforcing the perimeter of these openings.
- Understanding the behavior of FRP-strengthened systems helps improve failure mechanisms, which are typically brittle under cyclic loading.
- Current design codes provide reliable guidance for FRP strengthening and are expected to play an even more significant role in the next generation of standards.
- The application of FRP systems requires specialized training for the technical personnel involved in on-site implementation.
- Although the cost of FRP strengthening remains relatively high compared to traditional methods, this limitation is often offset by the numerous advantages of FRP systems, including their lightweight nature, ease of installation, minimal impact on structural mass, and high efficiency in improving structural performance.

Data accessibility:

There are no datasets associated with this study that require public deposition. However, all numerical models, analysis scripts, and computational codes used in this work are available from the corresponding author upon reasonable request

Declaration of AI use

AI tools (including ChatGPT) were used exclusively for improving formulation, grammar, and clarity of the text, and not for generating scientific content, data analysis, conceptual development, or interpretation of results. All scientific ideas, methods, data processing, calculations, and conclusions were fully developed by the authors.

Authors' contributions:

NK, - Conceptualization; methodology; supervision; validation; writing—review and editing;

EK,-Formal analysis; numerical modelling; investigation; writing—original draft; writing—review and editing; YM,- Data curation; resources; investigation; visualization; writing—review and editing.

Authors's approval

All authors have read and approved the final version of the manuscript and agree to be held accountable for all aspects of the work.

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A MULTI-CRITERIA METHODOLOGY FOR THE INTEGRATION OF RISK ASSESSMENT INTO SPATIAL PLANNING AS A BASIS FOR TERRITORIAL RESILIENCE: THE CASE OF SEISMIC RISK

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ABSTRACT

Rapid urban development and the continuous demand for space have intensified pressure on land resources. The increasing need for "usable" space, regardless of its purpose, has led to the overutilization of existing areas and the creation of new ones, both of which significantly increase exposure to natural hazards. The manner in which communities and urban systems respond to natural disasters is closely linked to their levels of economic and technological development, as well as to the availability of reliable data. Developed countries generally possess the capacity to implement mitigation strategies prior to disaster events, whereas such capacities are often limited or absent in developing and low-income countries. Gaillard and Mercer (2012) stated that disasters disproportionately affect marginalized populations that have limited or no access to resources and protective mechanisms. This paradigm highlights the necessity of developing preventive strategies centred on communities directly affected by the consequences of such natural events. The present research aims to analyse an approach for integrating disaster risk information into spatial planning instruments to promote an inclusive Disaster Risk Reduction (DRR) process. The study proposes a multi-criteria risk assessment methodology at the local scale for seismic events. The primary objective of this paper is to provide an adapted approach to risk management and decision-making by incorporating appropriate strategic risk reduction measures, policies, prioritization mechanisms, and funding allocation strategies.

***Keywords*:** earthquake, resilience, risk assessment, urban system, vulnerability

1. INTRODUCTION

1.1 Motivation and problem statement

Adapting to and living with natural hazards remains one of society's greatest and most persistent challenges, given the growing need for the development of new technologies, social structures, and cultural practices to ensure survival. According to Ritchie and Roser (2014), natural disasters have caused approximately 47,000 fatalities and affected 186.5 million people worldwide. Low- and middle-income countries are disproportionately affected by natural disasters, largely due to inadequate infrastructure (Ritchie and Roser, 2014). While losses from hazards such as floods, storms, and heatwaves have decreased as a result of improved infrastructure and early-warning systems, earthquakes remain a major concern because they can cause severe damage with little or no warning. This statistical overview highlights two key concepts related to natural hazards and the behaviour of human and urban systems: **exposure** and **vulnerability**. Not every hazard results in a disaster; rather, disasters occur when hazards interact with specific vulnerabilities in the built environment, leading to catastrophic outcomes. Historically, disaster management efforts focused primarily on emergency response and post-disaster reconstruction. However, in recent decades there has been a paradigm shift toward prevention and preparedness strategies that emphasize risk reduction before disasters occur (Sutanta *et al*. 2010).

Preventing damage before an event occurs requires anticipating the potential impacts that such an event may generate within a given area—an approach known as *ex-ante* analysis, which is central to risk analysis and assessment. The overall process of assessing and reducing risk involves multiple disciplines and perspectives; therefore, an integrated and cross-sectoral approach, together with collaboration among actors at different governance levels, is essential.

Based on extensive research on disaster-related issues, Gaillard and Mercer (2012) identify two major paradigms: the hazard paradigm and the vulnerability paradigm. The former suggests that disasters occur as a result of inadequate risk perception among affected populations, who consequently fail to adapt and reduce their exposure. This perspective represents a generalized and event-centred approach. In contrast, the vulnerability paradigm emphasizes that disasters disproportionately affect

marginalized populations who lack access to resources and means of protection.

Within this second paradigm, Disaster Risk Reduction (DRR) is considered effective only when it adopts an inclusive approach characterized by:

- the integration of both scientific and local knowledge,
- the combination of top-down and bottom-up actions; and
- the promotion of collaboration among a broad range of stakeholders.

The absence of such inclusive processes, combined with increasing levels of vulnerability, is widely regarded as one of the main reasons why disasters continue to increase worldwide.

Spatial and urban planning play a vital role in risk assessment because they regulate land use and territorial organization, making them crucial instruments for reducing exposure and vulnerability to hazards. Planning instruments also serve as a fundamental link in bridging the gaps that hinder inclusivity in DRR processes. Suri *et al*. (2020) stated that achieving resilient cities requires planners to place disaster risk reduction at the core of sound urban development—an integration that, despite its importance, remains limited in practice.

1.2 Purpose of the study

Over the past decades, a substantial body of research has been devoted to assessing the risks associated with hazardous events. Existing approaches vary from single-hazard assessments, which analyse the risk posed by one specific hazard, to multi-hazard approaches, which examine several hazards simultaneously and consider their combined effects on a given area. The selection of an appropriate approach depends largely on the required level of detail and the availability of data, based on which risk can be estimated in qualitative or quantitative terms. Regardless of the method employed, the entire process must be viewed holistically. Accordingly, variables of different natures must be integrated and harmonized to generate outputs that are meaningful and applicable for decision-making bodies and actors.

Adopting a holistic perspective raises several challenges, primarily concerning the way information is communicated and interpreted among experts from different disciplines. Among these, spatial planners—as highlighted in the previous section—play a crucial role, as they serve as a

fundamental link in the practical application of risk assessment. Their outputs tend to be more tangible and comprehensible from a decision-making standpoint. From this perspective, the key challenge lies in integrating risk assessment information into spatial planning in a manner that is clear, reliable, and translatable into planning policies and land-use regulations, while also assessing the potential implications of such integration for planning systems and instruments.

The general objective of this research is to assess seismic risk at a local territorial scale. Given the range of methodologies available in the literature, a realistic aim is to examine existing methods and theories, interpreting them in a way that enables their practical integration across different levels and among diverse stakeholders.

The specific objective of the study is to integrate a semi-quantitative risk assessment model into spatial planning instruments through the use of inclusive variables within a multi-scale framework. Such a multi-scale approach is expected to facilitate the integration of Disaster Risk Reduction (DRR) into urban planning processes. This integration can promote stakeholder collaboration, bridge the gap between scientific and local knowledge, and enhance both communication and risk perception within communities.

Based on these objectives, the main research question is formulated as follows:

How can risk knowledge be effectively integrated into spatial planning instruments to promote an inclusive Disaster Risk Reduction (DRR) process?

1. To address this overarching question, several complementary research questions are proposed to guide the investigation and support the achievement of the study's final objectives:
2. How can multi-scale information be combined to define different levels of risk?
3. Which parameters are the most inclusive and adaptable to local contexts for defining seismic risk?
4. What are the most effective ways to produce and communicate risk information for decision-making purposes and to enhance risk perception within communities?

2. PROPOSED METHODOLOGY

The proposed methodology for assessing and integrating seismic risk information into spatial planning can be summarized in the Figure 1:

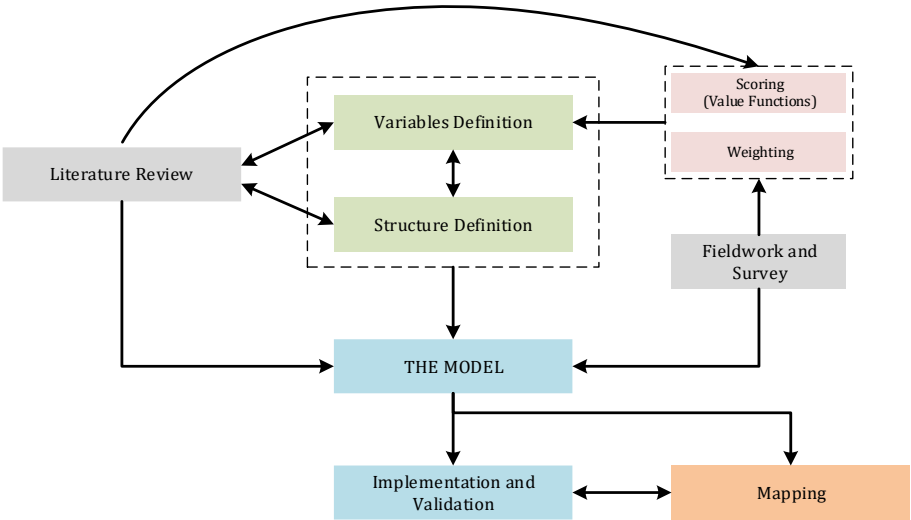

Fig. 1. An overview of the methodology.

It is based on the risk-index approach, in which risk and its constituent elements are derived through a scoring process using ordinal scales. This approach is more rigorous than a purely qualitative method but does not reach the level of a fully quantitative one, since risk is expressed through comparative scores rather than explicit probabilistic terms. Therefore, it is categorized as a semi-quantitative approach.

Risk indices are typically used in situations where data limitations make it difficult to quantify the components of risk, and where the assessment covers large geographical areas. The input data are derived from a detailed analysis of the system; therefore, any index-based risk assessment must be preceded by a comprehensive understanding of the sources of risk. At this stage, additional analytical tools such as fault-tree analysis or event-tree analysis can be employed to structure the problem and illustrate the relationships between risk components and their corresponding indicators across different levels.

In the field of disaster risk reduction (DRR) and natural hazard management, information is frequently presented in a spatial format, often

through maps. When the available input consists of multiple geographical datasets used for selecting alternatives and supporting decision-making, the process is referred to as Spatial Multi-Criteria Evaluation (SMCE). SMCE serves as a complementary method to existing qualitative and quantitative approaches to risk analysis and zoning. In the present study, local-scale risk indices are combined with SMCE to produce a single, integrated risk value, which can then be used for decision-making purposes or preliminary evaluations.

Based on the relevant literature (Eastman, 2005; Sinha *et al*. 2014; Patel *et al*. 2017), the procedure for converting various parameters into a single risk index—suitable for subsequent decision-making—comprises four main steps:

Step 1 – Structuring the Decision Problem:
Step 2 – Standardization:
Step 3 – Weighting (Prioritization)
Step 4 – Aggregation:

2.1. Structure definition

For the purpose of this research, the structure is divided into four levels, with the addition of a fifth level, as shown in Fig. 2. Each variable has been selected to best represent the constituting elements of seismic risk.

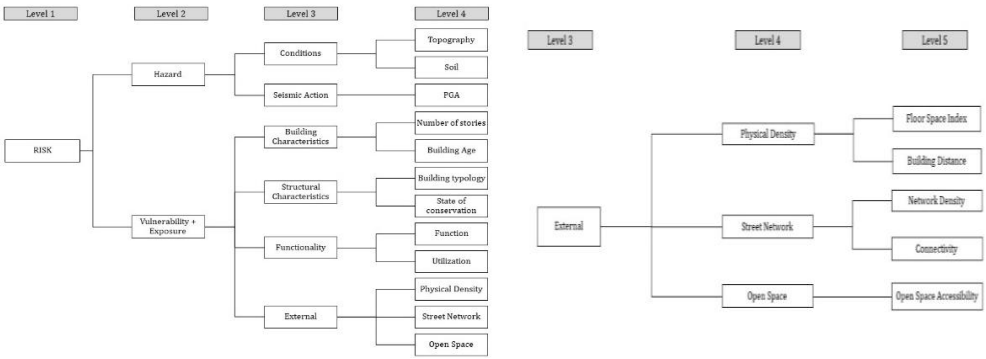

Fig. 2. Proposed hierarchical structure for the assessment of seismic risk.

The literature provides numerous studies addressing seismic risk—ranging from qualitative to advanced quantitative methodologies—each employing its own set of indicators. Many of these indicators are common

across approaches, while others differ, often depending on the scale of the problem under consideration.

From a structural perspective, risk assessment focuses on the building scale, aiming to predict potential consequences for individual structures. Such assessments require extensive data at this scale. For example, Kassem *et al.* (2020) examined indices and methodologies used in seismic risk assessment to quantify the degree of damage to structural elements or entire structural systems. Parameters such as the organization of the structural system, plan configuration, vertical irregularities, elements with low ductility, and non-structural components are analysed and quantified to evaluate seismic risk.

In contrast, from an urban planning perspective, the focus shifts toward integrating building-scale assessments into a broader urban context to support decision-making and the development of preventive strategies. Consequently, the indicators employed at this level are more comprehensive, aiming to bridge the gap between scales. For planning purposes, both physical and non-physical indicators are considered to evaluate economic and social vulnerability—for instance, population density, social disparity, and development level. In the proposed hierarchy, this interrelationship between scales is expressed through the combination of vulnerability and exposure indicators that relate to the building scale (e.g., building and structural characteristics) with external indicators such as physical density, street network, and open spaces. Additionally, functionality-related indicators (e.g., function and utilization) are included to account for the level of human exposure and the importance of critical structures.

2.2. Standardization

Decision-making processes often require the integration of multiple variables of different natures, the combination of which produces alternative scenarios. Based on these alternatives, decisions are made to select the most acceptable option in terms of objectives and feasibility. Integrating numerous variables to define the best and/or worst scenarios necessitates an analysis in which these variables are compared and combined. To make two or more variables comparable, a scaling or standardization process is required, converting them into a common, unitless scale. This transformation—from variables of different types into unified, comparable measures—is known as the standardization process.

Standardization can be achieved using mathematical equations represented graphically as value functions, which Beinat (2012) defines as:

"*...mathematical representation of human judgements.*"

For each selected parameter in the proposed structure, the tendency, range, shape, and corresponding mathematical expression are defined. The outcomes of the four-step analysis are expressed through the respective value functions. In this research, a direct relationship is established in which higher standardized values correspond to higher levels of risk. In other words, standardized values approaching 1 represent the most critical or unfavourable conditions from the decision-maker's perspective. The standardization process for two variables is illustrated in the Figure 3.

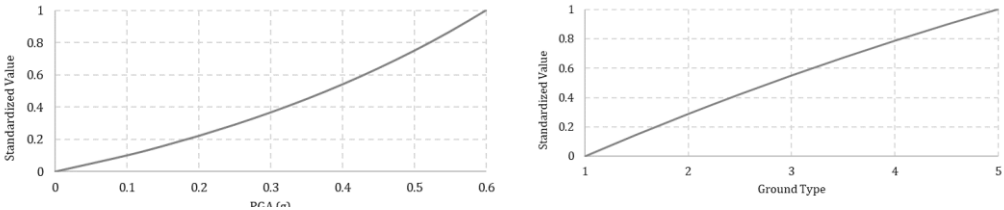

Fig. 3. Value functions for PGA (left) and Ground Type (right).

2.3. Prioritization

Similar to decision-making processes that involve multiple criteria and sub-criteria for evaluating alternatives, the process of risk assessment also requires the consideration of several criteria. As previously noted, incorporating multiple criteria into an analysis necessitates their comparison to ensure sound and consistent decision-making. In any given analysis, a decision-maker may regard certain aspects or criteria as more relevant or influential than others, thereby assigning them greater impact on the outcome. The relative importance of these criteria is commonly referred to as their weight.

One of the most widely used techniques for assigning weights is the Analytical Hierarchy Process (AHP), developed by Saaty (1980). The core of this method lies in the construction of pairwise comparison matrices at each hierarchical level. A key advantage of AHP is that its results can be verified through the Consistency Index (CI) and Consistency Ratio (CR), both derived from the order (n) of the developed matrix.

Weights are assigned from the lowest level of the hierarchy upward, by comparing elements at the same level. The determination of the relative importance of each variable is based on a review of previous studies and extensive literature, combined with expert opinions obtained through a simplified survey consisting of 13 questions. The following matrix presents the pairwise comparison used to determine the relative weight of building age compared to the number of storeys.

Table 9. Pairwise comparison matrix of the "Building Characteristics" elements

	Building Age	**No. Storeys**
Building Age	1.00	3.00
No. Storeys	0.33	1.00
Total	1.33	4.00

2.4. Aggregation and Risk Categorization

The procedures of standardization and weighting at each level of the defined hierarchy are followed by the aggregation process. During aggregation, all the information is combined to produce a final decision model. In the context of decision-making, this model represents the alternative, while for the purpose of this dissertation, it corresponds to the risk level.

One of the most widely applied aggregation methods is the Weighted Linear Combination (WLC), in which each standardized factor is multiplied by its corresponding relative weight, and the results are summed to obtain the final outcome. The following equation may be used to evaluate alternatives (Malczewski, 2000):

$$V(x_i) = \sum_j w_j v_j(x_i) \qquad \text{(Eq. 1)}$$

where *wj* is the normalized weight such that ∑wj=1, vj(xi) is the value function for the *j*-th parameter (attribute); V(xi) represents the overall value of the alternative or main objective, based on the value of the j-th attribute.

The interpretation of the risk results obtained in the form of indices, according to the aforementioned analysis, is performed through a categorization process. This process involves dividing and grouping the results into predetermined categories. Each category has a defined range (in terms of standardized values), and based on where a specific result falls, the corresponding category is assigned. Several studies and standards, including ISO 31010 (ISO 2009), recommend that consequences and severity levels be categorized using a scale of three to five classes. It is generally accepted that the greater the number of categories, the more refined and representative the judgment of the actual situation in terms of vulnerability and risk levels. Based on the literature review and expert consultation, it was determined that four classes will be used to categorize the level of risk.

Table 2. Risk categorization based on four classes

Risk level	Range	Description
R1	$R \leq 0.2$	LOW
R2	$0.2 < R \leq 0.4$	MODERATE
R3	$0.4 < R \leq 0.7$	HIGH
R4	$R > 0.7$	EXTREME

3. IMPLEMENTATION

The proposed methodology was implemented in two case studies: the first in the historical city center of Guimarães, Portugal, and the second in the city of Lezhë, Albania. Each selected case study represents a distinct urban context. The first area, a UNESCO World Heritage Site, is characterized by historical buildings with traditional construction features, while the second illustrates a modern, rapidly developing urban environment marked by high-rise buildings and a complex street network. The outcomes of the implementation demonstrate that the proposed approach is feasible, adaptable, and easily applicable, regardless of context. In this way, one of the main challenges of holistic risk assessment approaches—namely, their context-specific nature—is effectively addressed, making the methodology transferable and scalable across different territorial and urban settings.

The results for both case studies are presented in the form of risk maps. As expected, Guimarães exhibits a combination of low hazard with high vulnerability, whereas Lezha shows a combination of high hazard and medium to high vulnerability, resulting in a high overall level of seismic risk for most buildings.

Fig. 4. Risk map for the city centre of Guimarães (left) and Lezha city (right).

4. CONCLUSIONS AND RECOMMENDATIONS

This research focused on addressing the existing gaps in disaster risk reduction (DRR) related to knowledge exchange, the integration of top-down and bottom-up approaches, and the collaboration and coordination among a broad array of stakeholders. Considering the increasing need for an inclusive DRR framework, the study proposed an updated methodology capable of integrating specific variables that combine, first, information across different scales (building and zone), and second, data derived from different disciplinary perspectives—engineering and spatial planning. The primary objective was to generate essential and effective information that could be represented spatially and used as an input for preliminary decision-making processes. Given the large number of potential variables, a selection procedure was applied based on three key criteria: complexity, information availability, and importance.

The findings demonstrate that a multidisciplinary approach necessarily requires a multiscale framework, ranging from the operational scale (individual buildings) to the strategic scale (urban zones). While a detailed building-scale analysis provides a comprehensive understanding of expected damage from potential seismic events, it lacks contextual insight into the relationship between individual structures and their

surrounding urban environment. This broader perspective is critical not only during the emergency response phase but also in post-disaster recovery, as it allows for the generation of alternative strategies that can accelerate and optimize reconstruction processes. The outputs of this research aim to enhance risk perception and foster collaboration among stakeholders, addressing key challenges identified by Gaillard and Mercer (2012) in managing contemporary disaster risks.

With respect to the integration of risk knowledge into planning instruments, the study concludes that a multiscale approach is essential for promoting inclusive DRR processes. This approach enables the combination of context-specific local knowledge with generalized scientific data, bridging the gap between top-down institutional frameworks and bottom-up community-based actions. Data collection and processing at the local level provide valuable inputs for both national and municipal authorities, while regional and national coordination ensures consistency and scalability. Such an approach necessitates the involvement of a wide range of stakeholders, including local communities, institutional authorities, and scientific experts across the physical and social disciplines. It is recommended that the results of this research, after appropriate filtering and validation by local and national institutions, be made accessible to the public to support dissemination, awareness, and education. By adopting an open, transparent, and user-friendly structure, communities can be empowered and no longer marginalized in terms of information access and protection measures.

Future developments may involve the integration of additional variables to account for social, environmental, and economic aspects of risk, thereby transitioning toward a more holistic approach. From this perspective, the proposed model is flexible and adaptable, allowing for the inclusion of new parameters or hierarchical levels. The tool, in the form of an application or software platform, can serve multiple purposes: i) for specialists, as a means to assess and map seismic risk; ii) for local institutions, as a basis for prioritizing interventions; and iii) for communities, as a mechanism to raise awareness and improve risk perception.

Data accessibility

All Data supporting the findings of this study are available within the article and from publicly available sources cited in the references.

Declaration of AI use

No artificial intelligence tools were used in the writing, analysis and data processing of this research.

Author's contribution

The author was solely responsible for the conceptualization, data collection, analysis and preparation of the manuscript.

Conflict of interest

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SCIENCE INFORMATION

THE PERSPECTIVES OF PALEOGENETICS IN ALBANIA: INSIGHTS FROM FOSSIL AND SEDIMENTARY DNA

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Paleontology, sedimentology, and DNA are closely connected through a common objective: to understand, as comprehensively as possible, the evolution of life on Earth. Paleontology, the science that studies fossils, directly provides morphological evidence of organisms that lived in the past, while the study of ancient DNA (*aDNA*) from fossils and sediments enables the investigation of genetic relationships between extinct and extant, as well as their interactions with the environments in which they lived. Advances in DNA sequencing have revolutionized the paleogenetics, an interdisciplinary field that combines paleontological methods with molecular biology, thereby facilitating clarification of evolutionary processes over long geological timescale. Consequently, the relationship between paleontology and DNA can be considered almost symbiotic, and indispensable, as both disciplines collaborate to reconstruct, in detail, the biological past of our planet. Paleogenetics relies on the analysis of ancient DNA (*aDNA*) extracted from fossils, bones, teeth, mummified tissues, and other biological remains, as well as from sediments, using modern molecular biology techniques *such as polymerase chain reaction* (*PCR*) and high-precision genomic sequencing. The analysis of DNA extracted from relatively well-preserved fossils, such as those of *Coelodonta antiquitatis* (Figure 1), *Mammuthus primigenius* (Figure 2), or *Homo neanderthalensis* (Figure 3) and other prehistoric animals preserved in the permafrost deposits in Siberia, Alaska, or Canada, provides valuable insights into genetic structure, biological adaptations,

diseases, migration patterns, and interactions among prehistoric populations. In practice, paleogenetics enriches paleontology by transforming fossils from simple “morphological objects” into biological archives capable of revealing, at the molecular level, the evolutionary history of animal and human life. In this integrated approach, paleontology supplies the stratigraphic, chronological, and morphological framework, while paleogenetics contributes genetic evidence that validates or reformulates evolutionary hypotheses, together enabling a more comprehensive reconstruction of the history of life on Earth.

Fig.1: Coelodonta antiquitatis,
Encyclopedia Britannica. www.britannica.com

Fig. 2. *Mammuthus primigenius*,
drawing by Kennis, 1999.

Fig 3. Neanderthal skull, Tabun Cave, Israel,
The Israel Museum, Jerusalem. Wikipedia. www.wikipedia.org

In the study of biological evolution, *paleontology* and *genetics* represent two fundamental disciplines that provide independent yet deeply interconnected lines of evidence. *Fossil records* remain among the most of biological transformations across geological eras. Fossils are found within

well-defined sedimentary strata, dated using radiometric methods and stratigraphically correlated on a global scale.

Generally, their order of appearance corresponds to an evolutionary pattern of increasing complexity, from simple to more elaborate organisms, though exceptions and discontinuities do exist. The correlation of fossil-bearing strata from distant regions has made it possible to reconstruct a global chronology of life on Earth. In this context, transitional forms between major taxonomic groups, such as *Archaeopteryx* or *Tiktaalik*, have exceptional scientific value, offering insights into the mechanisms of species transformation. The distribution of fossils follows precise ecological and temporal rules, where some species are frequently found together, while others never co-occur, suggesting biological succession and replacement through geological time.

Modern *genetics* and, more recently, *paleogenetics*, have greatly expanded the possibilities for testing these paleontological hypotheses. Genetic, molecular, and morphological similarities between organisms are interpreted as evidence of *common descents*, and comparative genomic analysis now allows the construction of *phylogenetic trees* that broadly confirm the succession observed in the fossil record. In particular, paleogenetics has revealed unexpected continuities and interbreeding among apparently distinct species, such as *Homo sapiens*, *Neanderthals*, and *Denisovans*, offering a molecular perspective on evolutionary processes. However, this concordance between paleontology and genetics is not without challenges, as in some cases the fossil record reveals periods of "stasis," during which species appear to remain morphologically unchanged over long intervals. Similarly, the sudden emergence of major biological diversity—such as the *Cambrian explosion*—continues to raise questions regarding the timing and mechanisms of evolution.

Thus, the study of the relationship between *paleontology* and *DNA* is particularly valuable today for its ability to reconstruct the evolution of species, population migrations, biological adaptations, and environmental changes over time. In Western and Northern European countries, *paleogenetic research* is highly developed, with advanced academic centers using modern sequencing and bioinformatics technologies to analyze fossil DNA, especially from prehistoric human and animal remains. Major interdisciplinary projects carried out in countries such as France, Germany, the United Kingdom, and the Scandinavian countries have produced significant results concerning the origin and spread of modern humans, their interactions with Neanderthals, and the ecological

changes that occurred during the *Pleistocene* and *Holocene*, including shifts in characteristic flora and fauna.

In Albania, research is still developing, with most activity focused on classical *paleontology*, *stratigraphy*, and *sedimentology*. Although local infrastructure for ancient DNA (*aDNA*) studies remains limited, promising archaeological sites—especially in southern Albania—offer valuable opportunities for expanding paleogenetic research in the region, thereby contributing to the understanding of human evolution in the Balkans, a crucial corridor in prehistoric migrations.

Moreover, the Pleistocene–Holocene sedimentary deposits of the Albanian Alps (Valbona, Theth), which contain glacial and moraine sediments; the valleys of the Drin, Vjosa, and Seman rivers, with fluvial terraces; the Korça Basin, with lacustrine and peat deposits; the Adriatic coastal zone between Buna and Vlora, with marine and lagoonal sediments; and the mountain piedmonts, where alluvial cones develop, may all represent ideal settings for paleogenetic analyses through the study of fossil and sedimentary archives.

In addition, *cave sedimentary deposits* in Albania can provide highly valuable material for *paleogenetic DNA* studies due to the relatively stable environmental conditions that allow long-term preservation of biological remains. Relevant examples include the *Cave of Pellumbi*, where cave bear fossils and Paleolithic habitation traces have been discovered, as well as other deep caves in northern Albania with complex stratigraphy. These cave deposits offer opportunities for extracting DNA from bones, teeth, and other organic remains, although success depends on the preservation state of the material and on strict contamination control. While *speleological* and *archaeological* research in Albania is relatively well developed, direct genetic studies of human and animal DNA from these deposits remain limited, indicating significant potential for future research in *paleogenetics*.

With regard to *ancient DNA (aDNA)*, it is well established that it represents one of the most revolutionary, yet fragile, areas of molecular biology, because DNA molecules are highly unstable and rapidly degrade after an organism's death as a result of *hydrolysis*, *oxidation*, and *microbial activity*. Its survival depends strongly on environmental conditions, particularly low temperatures, dryness, and the absence of oxygen. In such favorable settings, such as cave sediments or Siberian permafrost, DNA fragments can persist for more than one million years. The oldest analyzed sequences originate from the teeth of Siberian mammoths dated to

approximately *1.2 million years*, whereas in temperate climates the realistic limit of DNA preservation does not exceed about *100,000 years*.

The *Pleistocene–Holocene* time frame represents the ideal geological interval for DNA preservation, and the integration of *paleontology* and *sedimentology* focused on this period with *genetics* provides an essential interdisciplinary framework for understanding the recent evolution of species, especially fauna and hominins, as well as paleoecological conditions. In this context, *paleogenetics* plays a central role, allowing the extraction and analysis of ancient DNA from well-preserved fossils recovered from permafrost, caves, or even arid environments. As noted above, this geological interval offers optimal conditions for genetic preservation, which is why most paleogenetic studies focus on species dating from the Late *Pleistocene* and Early *Holocene*, such as mammoths, woolly rhinoceroses, cave bears, and various ancient and modern human populations. Correlating genetic data with paleontological, sedimentological, and archaeological evidence enables the reconstruction of population dynamics, migrations, ecological adaptations, selective pressures, and extinction processes. In humans, this approach has allowed the identification and sequencing of *Neanderthal* and *Denisovan* genomes, as well as the detection of genetic admixture between these groups and the emergence of *Homo sapiens*. Similarly, in fauna, *paleogenetics* has contributed to understanding the factors that led to the extinction of large species during the *Pleistocene–Holocene* transition, including climatic impacts and anthropogenic pressures. The analysis of ancient DNA from the *Pleistocene–Holocene* interval has thus revolutionized our understanding of species evolution and ecological dynamics.

However, DNA cannot be extracted from every fossil. Fossil DNA, known in the scientific literature as *ancient DNA (aDNA)*, is one of the most groundbreaking areas of molecular biology and paleogenetics, but the chemical fragility of DNA and the environmental conditions under which it has been preserved over geological time pose serious challenges. DNA is an unstable macromolecule that begins to degrade immediately after an organism's death under the influence of *hydrolysis*, *oxidation*, and *microbial activity*. Without exceptional preservation conditions, its structure undergoes fragmentation and irreversible alterations, making reconstruction impossible after long intervals. The maximum theoretical survival time of DNA is estimated to be approximately 1–1.5 million years, but only in exceptional environments, such as the cold, dry, oxygen-free

Siberian permafrost, where molecular degradation is drastically slowed, allowing the preservation of sufficient fragments for sequencing.

The oldest DNA analyzed to date originates from the teeth of mammoths discovered in northeastern Siberian permafrost (Kornienko *et al*. 2018; Calábková *et al.* 2022), dated to approximately *1.2 million years*. In temperate climates, especially in cave deposits, genetic reconstructions have been achieved for material up to *50,000–100,000 years* old, as in the case of *Denisovans* and *Neanderthals* (Reich *et al*., 2010; Prüfer *et al*. 2014; 2017). Classic examples include *Neanderthal* DNA extracted from bones preserved in cold European caves (Slon *et al*. 2017) and the genome of a Middle *Pleistocene* horse, approximately *700,000 years* old (Orlando *et al*. 2013), both of which confirm the decisive role of environmental conditions in preserving genetic information.

The main factors influencing DNA stability are *temperature*, *humidity*, *pH*, and the physical protection provided by the mineral matrix of dense bones, such as the petrous portion of the temporal bone or teeth. In temperate or tropical climates, where humidity and thermal variation accelerate degradation, genetic material is typically destroyed within tens of thousands of years, drastically limiting analytical potential. In conclusion, although fossil DNA offers a unique window into the biological and evolutionary past of species, the temporal range for its study does not exceed, even under the most favorable conditions, *1–1.5 million years*. In most archaeological and paleontological contexts accessible to humans, the realistic threshold remains below *100,000 years*, as determined by chemical degradation and preservation conditions. Nevertheless, modern *next-generation sequencing* technologies make it possible to obtain reliable genetic data even from highly degraded samples.

Analyses of DNA from *sedimentary deposits* in caves and lakes have particularly high potential because these environments provide optimal conditions for long-term preservation of genetic material. Sediments protect DNA from mechanical degradation and exposure to harmful environmental factors, while stable microclimatic conditions—such as constant temperatures, relative humidity, and often *anoxic* settings—slow chemical and biological degradation processes, including *hydrolysis*, *oxidation*, and *microbial activity*. Moreover, these deposits accumulate organic matter from multiple sources, including direct plant and animal remains, feces, hair, pollen, and organic material transported by water and wind, enabling detailed reconstructions of past fauna, flora, and microbial communities. The stratigraphy of these sediments provides a precise

temporal framework, allowing DNA to be correlated with climatic changes, species migrations, and human activities. Consequently, cave and lake sediments constitute extensive "genetic archives" capable of revealing past biological diversity and ecological dynamics at both community and regional scales. The combination of physical protection, favorable chemical conditions, and integrated accumulation of biological material makes these environments among the most promising for *paleogenetic* studies.

Animal *ancient DNA (aDNA)* from caves represents a crucial source of information for reconstructing extinct faunas and understanding past ecological and climatic dynamics. Cave deposits—including sediments, bones, teeth, hair, and fat residues—can preserve aDNA from animals that lived nearby or were transported by predators, humans, or natural processes. Analysis of this *sedimentary DNA* allows species identification even in the absence of visible fossils, opening new avenues for paleogenetic research. Recent studies have detected aDNA from mammoths, bison, horses, and woolly rhinoceroses in Siberian caves older than *50,000 years*, providing detailed insights into *Pleistocene* faunas (Vartanyan, 2008; van der Valk *et al*. 2021). In *Denisova Cave* (Altai Mountains), animal aDNA has helped reconstruct archaic ecosystems and establish trophic relationships between hominins and contemporaneous fauna. European caves such as *Vindija* (Croatia) and *Scladina* (Belgium) have yielded aDNA from cave bears, wolves, rhinoceroses, and reindeer, confirming coexistence with *Neanderthal* populations. In the Balkans, fossil DNA studies remain limited, but the scientific potential is considerable: sedimentary deposits in Albanian caves may preserve genetic traces of glacial and postglacial faunas, including cave bears, hyenas, wild goats, deer, and bats. Analysis of animal aDNA provides insights into extinct ecosystem reconstruction, migration patterns, climatic adaptations, and interactions between human activities and natural habitats. Albanian caves therefore constitute a valuable geological, paleontological, and archaeological heritage, offering optimal conditions for the preservation of sedimentary aDNA.

In addition to cave sediments, *lake sediments* can also provide extremely valuable genetic information. The recovery of DNA from such deposits enables the reconstruction of *Holocene* vegetation and faunal diversity, offering detailed perspectives on ecological changes recorded over millennia. However, the study of fossil DNA faces major challenges related to contamination by modern DNA and chemical degradation of the

molecule, requiring rigorous extraction and sequencing protocols as well as carefully contextualized data interpretation. Recent research emphasizes that ancient DNA analysis complements, and in some cases corrects, traditional paleontological evidence, demonstrating that human and species evolution is a complex, multidimensional, and interconnected process.

aDNA from lake sediments (Willerslev *et al*. 2003) represents a powerful tool for reconstructing past ecosystems, biodiversity, and environmental changes, complementing traditional paleontological and paleoecological methods. *Sedimentary DNA* preserved in lacustrine deposits originates from plants, animals, and microorganisms that lived in or near the lake, as well as from organic matter transported by wind, water, or the activity of living organisms. Because this DNA can survive even in the absence of visible fossils, it enables the identification of species that leave no morphological traces. Analyses of lake sediment DNA (*sedaDNA*) provide high-resolution reconstructions of vegetation dynamics, faunal composition, and microbial communities over time, allowing the study of ecological succession, species migrations, and responses to climatic fluctuations during the *Holocene* and Late *Pleistocene*. Furthermore, integrating genetic data with sediment stratigraphy, pollen analyses, and geochemical proxies allows correlations between environmental changes, human activities, and ecosystem adaptations. In practice, lake sediment DNA analysis has been used to track changes in plant communities, monitor faunal variation in alpine lakes, and detect human-induced environmental modifications. In regions such as Albania, lake sediments offer particularly valuable opportunities for paleogenetic studies, as tectonic lakes, floodplain deposits, and peat layers can preserve DNA under stable, anoxic, or cold conditions.

The recovery of ancient DNA from lake sediments provides an innovative method for reconstructing biodiversity and ecological changes during the *Holocene*, surpassing traditional techniques such as pollen and macrofossil analyses and allowing the detailed study of plant and animal communities even in the absence of visible fossils (Pedersen *et al*. 2013; Parducci *et al*. 2017; Voldstad, 2020; Garcés-Pastor *et al*. 2022). Recent studies have demonstrated the effectiveness of this method in diverse regions. For example, analyses of DNA from lake sediments in northern *Fennoscandia* revealed that terrestrial plant diversity was significantly influenced by regional climate and soil nutrients, providing a detailed picture of vegetation change. In another study, DNA extracted from lake

sediments in *Ringhorndalen*, Norway, identified shifts in plant and animal communities throughout the *Holocene*, correlating them with climatic variability and human activities (Jia *et al*. 2022; Han *et al*. 2024). The method involves extracting DNA from sediment-core samples followed by sequencing to identify species present during different historical periods. This approach produces detailed temporal records of biodiversity and provides insights into how lacustrine ecosystems have fluctuated and adapted in response to climate change and human intervention.

In conclusion, ancient DNA analysis from lake sediments represents a powerful and versatile approach for studying *Holocene* lacustrine ecosystem evolution, offering detailed perspectives on the complex interactions between climate, environment, and human activity, and highlighting how these communities have adapted and transformed over millennia.

In Albania, the study of ancient DNA is still developing, with a primary focus on *human DNA* research, whereas sedimentary and paleontological DNA—namely, ancient DNA extracted from sediments or associated with fossils—remains far less developed, thus offering significant research opportunities. Regarding human DNA, recent advances include analyses of ancient genomes from southeastern Europe showing genetic continuity between *Bronze* and *Iron Age* populations and modern Albanians, as well as studies of mitochondrial and *Y-chromosome* haplogroups that reveal regional particularities while maintaining affinities with other European populations. In addition, research on skeletal remains from archaeological sites demonstrates the applicability of human DNA studies in the Albanian context.

Nevertheless, sedimentary and fossil DNA remain largely unexplored in Albania, despite the demonstrated success of these methods in other regions for recovering ancient DNA from diverse environments, providing data on past fauna, flora, and microorganisms, and contributing to paleoecological and environmental reconstructions. This approach is particularly relevant in Albania due to its complex geological setting—including mountainous regions, tectonic lakes, caves, and coastal plains—where well-preserved sediments may retain valuable genetic signals.

The synergy between *sedimentology*, *paleontology*, and *genetics* can yield integrated reconstructions linking stratigraphic and paleoecological data with genetic evidence, thereby providing a more holistic view of the past. In the Albanian context, with its complex geological history, this innovative approach could complement human DNA studies and enhance

understanding of how environments have influenced populations and ecosystems. Thus, *sedimentary paleogenetics* represents a unique interdisciplinary, methodological, and academic research opportunity capable of offering new perspectives on the biological and cultural evolution of the region.

The *Quaternary* deposits of Albania constitute a crucial geological archive for reconstructing past climates and environmental changes in the *Eastern Mediterranean*, as they provide valuable data for understanding active tectonics, crustal uplift, and the development of groundwater systems within extensive alluvial formations. Moreover, these deposits enable correlations between geomorphological evolution and archaeological settlement patterns. Although significant progress has been achieved through studies in *palynology*, *radiometric dating*, and *geomorphological mapping*, additional research is required to integrate Albania more fully into the wider Mediterranean and European *Quaternary* stratigraphic framework.

In Albania, the integration of *ancient DNA (aDNA)* studies into *Quaternary* research would significantly enhance multidisciplinary reconstructions of past environments, biodiversity, and human–environment interactions. *Sedimentary DNA (sedaDNA)* analyses could provide molecular evidence of past ecosystems by identifying plant, animal, and microbial species that inhabited specific climatic intervals, thereby complementing traditional paleontological and palynological data. Moreover, genetic variability patterns derived from *aDNA* would allow correlations between biological evolution and glacial–interglacial oscillations, elucidating adaptive responses and migration dynamics during *Quaternary* climatic shifts. Comparative genetic data from sediments, bones, or peat layers could also clarify regional biological continuity and connectivity between Albanian populations and those of the wider Balkan and Mediterranean regions, contributing to the reconstruction of dispersal routes and glacial refugia. Furthermore, integrating *aDNA* with geomorphological and archaeological evidence could document early human presence, pastoral activities, and agricultural transitions during the *Holocene*, aligning biogenetic signals with landscape evolution and settlement phases. Consequently, the application of *paleogenetic* approaches would transform *Quaternary* deposits from purely sedimentary archives into complex *biogeological* records capable of revealing the intertwined history of climate, life, and human occupation in southeastern Europe. Understanding the geology of *Quaternary* deposits

in Albania is essential for ancient DNA studies, as sedimentary contexts provide crucial information about preservation, stratigraphy, and the environmental conditions that influence the survival of genetic material over time. Therefore, the following section briefly presents key information regarding these deposits.

Quaternary Deposits in Albania: Stratigraphy, Depositional Systems, and Geomorphological Evolution

According to Xhomo *et al.* (2002), the *Quaternary* deposits of Albania represent one of the most extensive and diverse sedimentary archives in the region, occupying intramontane basins, river valleys, the *Adriatic* coastal plain, and mountain piedmonts. Their spatial continuity and lithofacies variability reflect the combined influence of active tectonics, climatic oscillations, sea-level fluctuations, and hydrographic reorganization throughout the *Pleistocene* and *Holocene*. Nearly all major genetic types of continental, transitional, and marine deposits are represented, including alluvial, proluvial, colluvial, glacial, lacustrine, swamp, lagoonal, deltaic, and coastal-marine facies. In many basins, these facies occur as composite successions (e.g., alluvial–proluvial, lacustrine–proluvial, lacustrine–alluvial), reflecting shifts in sediment supply, basin hydrology, and relief energy through time (Figure 4).

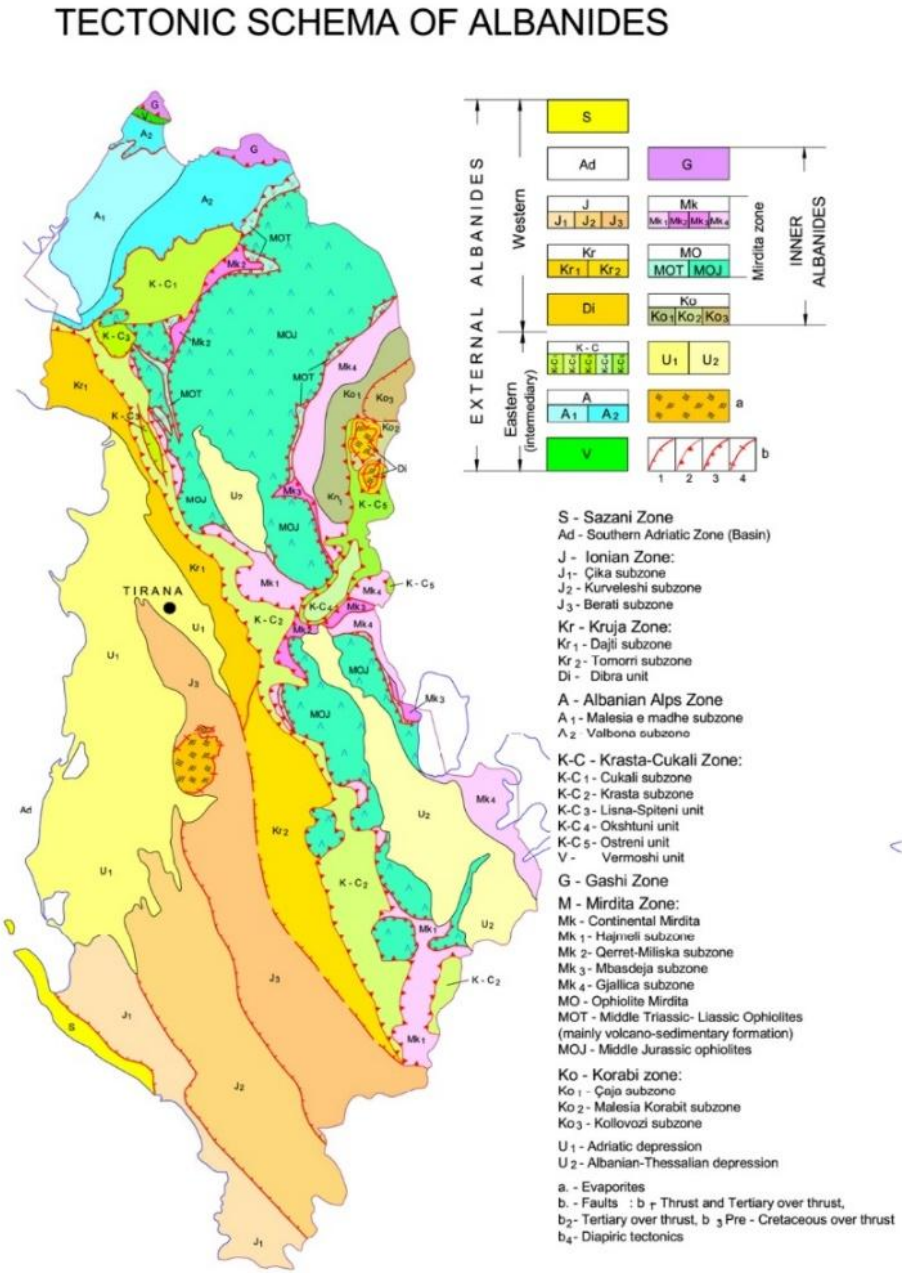
TECTONIC SCHEMA OF ALBANIDES
EXTERNAL ALBANIDES
Western
Eastern (intermediary)
INNER ALBANIDES
Mirdita zone
TIRANA
S - Sazani Zone
Ad - Southern Adriatic Zone (Basin)
J - Ionian Zone:
J1- Çika subzone
J2 - Kurveleshi subzone
J3 - Berati subzone
Kr - Kruja Zone:
Kr1 - Dajti subzone
Kr2 - Tomorri subzone
Di - Dibra unit
A - Albanian Alps Zone
A1 - Malesia e madhe subzone
A2 - Valbona subzone
K-C - Krasta-Cukali Zone:
K-C1 - Cukali subzone
K-C2 - Krasta subzone
K-C3 - Lisna-Spiteni unit
K-C4 - Okshtuni unit
K-C5 - Ostreni unit
V - Vermoshi unit
G - Gashi Zone
M - Mirdita Zone:
Mk - Continental Mirdita
Mk1 - Hajmeli subzone
Mk2 - Qerret-Miliska subzone
Mk3 - Mbasdeja subzone
Mk4 - Gjallica subzone
MO - Ophiolite Mirdita
MOT - Middle Triassic- Liassic Ophiolites (mainly volcano-sedimentary formation)
MOJ - Middle Jurassic ophiolites
Ko - Korabi zone:
Ko1 - Çaja subzone
Ko2 - Malesia Korabit subzone
Ko3 - Kollovozi subzone
U1 - Adriatic depression
U2 - Albanian-Thessalian depression
a. - Evaporites
b. - Faults : b1 Thrust and Tertiary over thrust,
b2- Tertiary over thrust, b3 Pre - Cretaceous over thrust
b4 - Diapiric tectonics

Fig. 4. Geological map of Albania.

1. Upper Pliocene – Early Quaternary

These deposits, reaching thicknesses of up to *150–200 m*, are predominantly lacustrine to mixed lacustrine–proluvial in character and are well developed in the basins of *Tropoja*, *Kukës*, *Peshkopia*, *Kolonja*, *Erseka*, and *Saranda*, where they unconformably overlie *Mesozoic* carbonate formations or the ophiolitic basement. The sedimentary successions typically consist of alternating clays, silts, sands, and conglomerates, locally containing peat lenses and freshwater faunal remains. Their internal architecture reflects the development of low-gradient basins influenced by periodic clastic influxes from surrounding highlands, recording the transition from the *Neogene* tectonic basin stage to the onset of *Quaternary* climatic instability.

2. Pleistocene

The Pleistocene represents the most geomorphologically expressive segment of the Quaternary, encompassing deposits formed during multiple glacial–interglacial cycles. The most diagnostic features are the extensive alluvial terrace systems preserved along major river valleys. In the Devoll, Osum, Shkumbin, Vjosa, Drin, and Kiri valleys, up to six terrace levels have been identified, rising 20–160 m above the present river channels. These deposits range from well-cemented conglomerates to coarse gravels and sands, reflecting alternations between high-energy transport phases and episodes of valley incision. Radiometric dating, archaeological evidence, and regional geomorphological correlations relate these terraces to the Günz, Mindel, Riss, and Würm glacial stages. Proluvial fans, slope breccias (*colluvium*), glacial moraines, and lacustrine–terrestrial sequences are also widespread. Glacial deposits are best preserved in the *Albanian Alps* and in the *Korab*, *Tomorr*, and *Nemerçkë* massifs, where cirques, terminal moraines, and unsorted till bodies indicate *Late Pleistocene* glaciation. In contrast, the piedmonts of *Gramoz*, *Tepelena*, *Koplik*, and *Erseka* host thick proluvial cones, locally exceeding *50–80 m* in thickness, formed during interglacial phases of intensified hydrodynamic activity.

3. Holocene

The Holocene succession records the most recent phase of landscape evolution and is particularly well represented in the Adriatic foreland.

Alluvial deposits, 10–30 m thick, fill the coastal plains of Shkodra, Lezha, Tirana–Ishëm, Lushnja, Fier, Vlora, and the Korça–Bilisht Basin. These deposits extend upstream along the major rivers, forming modern floodplains and low terraces. They consist mainly of fine sands, silts, and clays, in marked contrast to the underlying Pleistocene gravels, and constitute one of Albania's principal aquifer systems.

The subdivision of the Holocene into Early and Late (Historical) phases is supported by pollen and radiocarbon data from Maliq and Koplik, where lake, peat, and soil sequences record environmental changes between approximately 4500 and 2200 BC, including the earliest evidence of cultivated plants such as *Juglans*, *Olea*, and *Castanea*.

Coastal evolution over the last 5,000 years has been strongly influenced by sea-level rise, delta progradation, and river alluviation. During this time, the Seman, Shkumbin, and Vjosa deltas have migrated laterally, repeatedly modifying the shoreline and giving rise to lagoonal and swamp systems such as Karavasta, Narta, Tërbufi, and Topoja.

The karstic relief of Albania, developed on Mesozoic and Paleogene limestones, has promoted the formation of numerous caves, galleries, and sinkholes, many of which were frequented or inhabited by prehistoric humans and animals. For ancient DNA studies, the characteristics of the cave environment are crucial for the preservation of genetic material. Ideal sites should be minimally disturbed by recent human activity; as modern contamination can compromise sample integrity. Caves with stable microclimates, constant temperature, and humidity enhance DNA survival, while stratified sedimentary deposits, such as fine sands or clays, provide both physical protection and chronological context. Karstic caves, which are widespread in Albania, particularly those with limited human access, are especially suitable because they offer natural protection against environmental fluctuations and facilitate the accumulation of well-preserved faunal remains.

Even well-explored sites continue to provide valuable opportunities for ancient DNA research. Notable examples include Konispoli Cave, north of Saranda, one of the deepest caves in the Balkans, which preserves Pleistocene and Holocene deposits containing animal remains, shells, stone tools, and complex stratigraphic sequences suitable for sedimentary DNA analysis (Russell, 1999; Hansen, 2001; Harold *et al.*, 2006). In addition, during the 1980s, a cave near the town of Gajtan was discovered, yielding numerous faunal fossils (Fistani, 1987; 1990; 1991; 1993 (a) (b); 1995; 1996). Approximately 30–40 m in front of this cave, archaeologists

uncovered a large assemblage of Middle Paleolithic flint tools produced using Levallois and Mousterian techniques, together with Upper Paleolithic artifacts. Of particular interest are prehistoric animal bones, including *Macaca*, *Dicerorhinus*, *Ursus deningeri*, and *Canis lupus mosbachensis*, all dating to the Pleistocene (Fjalori Enciklopedik Shqiptar, Vol. III: N–Zh, 2009).

Microclimatic stability, absence of direct sunlight, and the presence of calcium carbonate contribute to the preservation of genetic material, making Albanian caves highly promising for future paleogenetic projects. These sites offer unique insights into Balkan faunal evolution, glacial migrations, and human–environment interactions during the Late Pleistocene and Early Holocene. In Albania, DNA from lake sediments can also be studied in environments favourable for genetic preservation, including tectonic and depression lakes such as Lake Prespa in the Korça region, Lake Ohrid (Wagner *et al.*, 2017) on the northeastern border, and mountain lakes in the Albanian Alps (Theth, Valbona), which provide stratified, cold, and stable depositional conditions. Additional promising environments include floodplains and lowland deposits along the Drin, Vjosa, Shkumbin, and Seman rivers, where Holocene terraces and floodplains preserve plant and animal DNA, as well as peat layers and small marshy lakes, particularly in the Korça Basin and lowland river plains.

As a future perspective, the integration of paleontology, sedimentology, and ancient DNA research holds great potential for reconstructing past ecosystems, biodiversity, and human–environment interactions in Albania. Although paleogenetic studies in the region remain at an early stage, the country's diverse Quaternary deposits, karstic caves, lakes, floodplains, and peat layers provide ideal conditions for the preservation of genetic material. These environments, characterized by stable microclimates, stratified sediments, and minimal modern disturbance, offer exceptional opportunities to recover DNA from fossils, sediments, and other organic remains. Future research could illuminate the evolutionary history of Pleistocene and Holocene faunas, trace human migrations and cultural development, and clarify ecological responses to climatic change. By integrating genetic, paleontological, archaeological, and geomorphological data, Albanian sites have the potential to become key reference areas for understanding biodiversity dynamics and human–environment interactions in the Balkans.

Declarations

Data accessibility: websites, platforms

Declaration of AI use: There has been no use of AI when writing the actual paper.

Author Contributions

AU, paleontologist – conceptualization, writing and development of paleontological and paleogenetic framework, including data synthesis and figure preparation.

AF, sedimentologist – sketch of the geological and sedimentological framework, figure preparation.

MP– contributed stratigraphic expertise and to the integration of the stratigraphic context within the manuscript. All authors reviewed and approved the final version of the manuscript.

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THE DOUBLE-EDGED HELIX: DNA, ARTIFICIAL INTELLIGENCE AND THE BIOSECURITY CHALLENGE[1]

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ABSTRACT

Biotechnology has many beneficial applications, but it can also be used, either maliciously (e.g. for the development of bioweapons) or inadvertently, to cause harm. It is therefore a so-called *dual-use* technology.

For fifty years, the Biological and Toxin Weapons Convention (BWC) has effectively prohibited the development, production, acquisition, transfer, stockpiling, and use of biological and toxin weapons.

During this period, an increasing number of countries have developed significant capacity and expertise in biotechnology research; however not all have adequate regulatory checks and controls in place.

Artificial Intelligence (AI) is another increasingly accessible *dual use* technology that can be applied for beneficial purposes, but also for harm.

Because multilateral (United Nations) agreements often lack binding enforcement mechanisms, rely heavily on voluntary compliance, and cannot easily monitor the rapidly evolving global research landscape, they are insufficient on their own to regulate and oversee possible breaches in biotechnology research norms and regulations.

Ultimately, it is up to *all of us* – through education, training, and a commitment to responsible scientific practices, and the leadership of scientific institutions, such as academies of science, to stand up for what is right and ensure that biological weapons are consigned to history.

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The United Nations Office for Disarmament Affairs defines biological weapons as those weapons that "disseminate disease-causing organisms or toxins to harm or kill not only humans, but also animals or plants"[2]. It further notes that

[1] Based on the presentation given during the Albanian Academy of Sciences 'DNA Day Conference' on 25 April 2025.

[2] United Nations Office for Disarmament Affairs, *Biological Weapons*, available at: https://disarmament.unoda.org/biological-weapons/ (accessed 19 March 2026).

"they can be deadly and highly contagious," and adds that "diseases caused by such weapons would not confine themselves to national borders and could spread rapidly around the world."

Historical examples

Biological warfare is not a new or modern phenomenon, although early methods were relatively crude. During sieges, for example, beehives were sometimes catapulted into castles to panic the defenders. When the hives shattered, the enraged insects caused chaos among anyone nearby. Other 'weapons' were hurled in this way, as well. During the 1346 Mongol siege of Caffa in Crimea, for example, plague-ridden corpses were reportedly launched into the defendants' midst. People fleeing the siege carried the plague bacillus with them through the Bosphorus and Dardanelles straits and into the Mediterranean (Zanders, 2022). This event is widely associated with the onset of the *Black Death* epidemic (1346-1353) in Europe and North Africa, which killed an estimated 50 million people.

During the Second World War – before the structure of DNA had been elucidated – many countries maintained active biological weapons programmes. As one example of the kind of experimentation taking place, in 1942, British government scientists detonated bombs containing anthrax spores among a flock of 80 experimental sheep on Gruinard, a 2km long and 1km wide island located off the west coast of Scotland. The sheep began to die within days of exposure.

Anthrax has long been considered a potential biological weapon because it can infect both humans and domestic animals. However, its spores are extremely resistant and can persist in the environment for decades. As a result, Gruinard remained off-limits to livestock for more than 40 years. Decontamination, which, involved the spraying of formaldehyde mixed with seawater, and the removal of contaminated topsoil, began only in 1986. The following year, a test flock of sheep was reintroduced and survived.

More recently, a notorious anthrax attack occurred in the United States in the aftermath of the terrorist attacks of 11 September 2001. In this act of bioterrorism, the US Postal Service unwittingly delivered envelopes containing anthrax spores, resulting in 22 confirmed or suspected cases of infection that included five deaths (Bush and Perez, 2012).

Introducing the Biological and Toxin Weapons Convention (BWC)

Formally titled *The Convention on the Prohibition of the Development, Production and Stockpiling of Bacteriological (Biological) and Toxin Weapons and on their Destruction*, the Biological and Toxin Weapons Convention (BWC) entered into force in March 1975. For fifty years it has effectively prohibited the development, production, acquisition, transfer, stockpiling and use of biological and toxin weapons[3].

The Age of Biotechnology

The BWC entered into force almost twenty years after the 1953 elucidation of the DNA double helix structure by Watson, Crick and Franklin – an event often regarded as the beginning of the Age of Biotechnology. Indeed, the Convention was opened for signature in 1972, the same year that the first complete gene sequence (encoding the coat protein of a bacteriophage) was published (Min Jou *et al.* 1972).

Just one year later, in 1973, the first genetically modified organism (GMO) was reported, when DNA from one bacterium was successfully transferred into another (Stanley *et al.* 1973). Progress accelerated further in 1983 with the invention of the Polymerase Chain Reaction (PCR) by Kary Mullis, who received the 1993 Nobel Prize in Chemistry for this work[4]. PCR is a technique for rapidly multiplying specific DNA fragments, even when they are initially present at very low concentrations in a sample. It has since become routine practice in many laboratories worldwide. During the 1990s, the emergence of commercial gene synthesis companies made it possible for researchers to order custom-designed DNA sequences by mail.

Another transformative advance came in 2012 with the discovery by Jennifer Doudna and Emmanuelle Charpentier of the CRISPR-Cas9 gene-editing system – one of several gene-editing platforms now available – for

[3] United Nations Office for Disarmament Affairs, *Biological Weapons Convention*, available at: https://disarmament.unoda.org/en/our-work/weapons-mass-destruction/biological-weapons/biological-weapons-convention (accessed 19 March 2026).

[4] Nobel Prize Outreach AB, *Kary B. Mullis – Facts*, **Nobel Prize**, available at: https://www.nobelprize.org/prizes/chemistry/1993/mullis/facts/ (accessed 19 March 2026).

which they were awarded the 2020 Nobel Prize in Chemistry[5]. Together, these technologies enable unprecedented precision and flexibility in how DNA can be studied, modified, and utilised. In practical terms, we can do almost anything we want with DNA!

But the crucial question remains: *should we*?

The double-edged helix

The ability to analyze and manipulate DNA has many beneficial applications across science and society.

Vaccines based on mRNA technology, for example, helped protect millions of people during the COVID-19 pandemic (Zheng *et al*. 2022)[6]. The first successful gene-therapy treatment was reported as early as 1990 (Rosenberg *et al*. 1990), while the first clinical use of CRISPR-based therapy to correct a genetic defect came in May 2025 (Ledford, 2025). Beyond medicine, DNA technologies have helped accelerate plant breeding programmes, enabling the development of disease-, pest- or drought-resistant crop varieties. These improvements can be achieved through traditional breeding, now recognized as relatively slow and labor-intensive; through marker-assisted selection, which uses DNA-based technologies to track desirable traits in offspring; or through genetic modification (GM). Most commercially available GM varieties have been modified to resist pest attacks, or are herbicide tolerant (AgBio Investor GM Monitor 2025)[7]. More recently, new varieties developed using CRISPR-based gene editing technology are hitting the market. In May 2023, for example, less bitter mustard greens were introduced in the USA (Mullin, 2023), and in 2024, the Philippines government announced that a reduced-browning banana variety developed using CRISPR technology had been approved for import, propagation and production in the country[8].

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[5] Nobel Prize Outreach AB, *The Nobel Prize in Chemistry 2020*, **Nobel Prize**, available at: https://www.nobelprize.org/prizes/chemistry/2020/summary/ (accessed 19 March 2026).

[6] A meta-analysis of 51 studies that concluded that "COVID-19 vaccines are highly protective against SARS-CoV-2-related diseases in real-world settings.

[7] GM crops are now grown on more than 200 million Ha of land across the world, with soybean, maize and cotton being the most widely grown species.

[8] FreshFruitPortal, "New non-browning bananas in the Philippines," 3 July 2024, available at: https://www.freshfruitportal.com/news/2024/07/03/new-non-browning-bananas-in-the-philippines/ (accessed 19 March 2026).

These examples are only the first of many improved crop varieties currently under development and field-testing world.

However, DNA manipulation and biotechnology also have harmful or malicious applications.

While the merits, or otherwise, of so-called de-extinction (Jacobs, 2025) remain debated, biological weapons – described in the preamble of the BWC treaty as "repugnant to the conscience of mankind"[1] – and are "universally seen as abhorrent and illegitimate" (UN, 2022).

Although no country is currently known to possess or deploy biological weapons, several recent 'notorious' cases of *bona fide* research projects have raised concerns that legitimate scientific work could aid malicious actors in their bioweapons research.

Why the 'Double-edged' Helix?

Case study 1: Gain of Function (GoF)

Gain of Function (GoF) research is generally defined as research in which an organism is genetically altered in a way that modifies the biological function of one or more of its gene products. For disease-causing organisms, this may include changes in pathogenicity, transmissibility, or host range.

In 2012, two laboratories independently reported experiments involving the H5N1 avian influenza virus. One was led by Yoshihiro Kawaoka at the University of Wisconsin-Madison, USA, (Imai, 2012) and the other by Ron Fouchier at the Erasmus University Medical Centre in the Netherlands (Schrauwen *et al*. 2018). Although H5N1 spreads easily among a number of bird species and can infect mammals, it is not usually transmissible between mammals. Both research teams overcame this limitation by repeatedly passaging the virus from one ferret to another. After several cycles, it was noted that the virus was better able to survive in ferret lungs and, crucially, became capable of being transmitted between ferrets without direct human intervention. In effect, the virus had become airborne, spreading via droplets when infected animals coughed or sneezed.

Because H5N1 can cause severe disease in humans, the evolution of a mammal-to-mammal airborne strain raised profound biosecurity concerns, particularly if such a virus were to escape – even accidentally – from the high-containment laboratories in which the research was conducted. Supporters of the work argued, however, that these

experiments could help guide the development of vaccines and antiviral drugs that would target the novel mutations that enabled airborne transmission.

Why the 'Double-edged' Helix?
Case study 2: Poxviruses

Poxviruses (family *Poxviridae*) are a group of double-stranded DNA viruses that infect a wide range of vertebrates and arthropods. For much of human history, smallpox was one of the most debilitating and deadly infectious diseases. Following a global vaccination campaign, the World Health Organisation officially declared smallpox to be eradicated in 1980, (WHO, 1980), although a small number of samples remain stored in nominated high security laboratories. Vaccination against smallpox was originally developed using the closely related – but milder in humans – cowpox virus.

Another poxvirus that infects a domesticated animal is horsepox. Although horsepox is not known to cause disease in humans, and is also believed to be extinct in nature, it does have a genome closely related to that of smallpox. In 2017, a team of Canadian researchers ordered a series of horsepox DNA fragments from a commercial supplier. Using standard molecular biology technologies, they assembled these fragments in the laboratory – and successfully recreated fully infectious horsepox virus.

Having demonstrated that this could be done, the concern is that the same approach could be used by others to reconstruct smallpox itself.

Legislation

We therefore return to the central question: We can now do almost anything we want with DNA – but should we?

To explore this, three additional questions must be considered:

- Is all knowledge inherently good?
- What checks and controls exist?
- Who possesses the knowledge and the capacity to conduct such work?

The first question raises deep philosophical issues that will not be addressed here.

With respect to the second question, many countries – particularly those with well-developed research systems – have established layers of oversight. These include legally binding laws and regulations, as well as 'bottom-up' approaches such as best practices guidelines, and research ethics frameworks and codes of conduct.

Following the H5N1 gain-of-function experiments described above, the European Academies' Science Advisory Council (EASAC) conducted a study that concluded that the necessary laws, rules, regulations and research integrity frameworks are in place in several (though not all) European Union (EU) countries, and that, overall, EU-based research in this area was being conducted responsibly (EASAC, 2015).

In the United States, regulatory oversight was comparatively less strict until the second Trump administration, when rules and regulations were tightened through an Executive Order (White House, 2025), although the precise implications – including how non-federally funded research will be regulated – remain unclear (Kupferschmidt, 2025).

To address the third question, it is important to recognise that an increasing number of countries are developing significant scientific capacity, including in biotechnology (CAS-TWAS Centre of Excellence in Biotechnology and Clarivate Analytics, 2016). Following the COVID-19 pandemic, many governments have also invested in high-containment biosecurity laboratories, arguing that such facilities are essential for studying pathogens that affect their populations. At the same time, advances such as PCR and gene-editing techniques have effectively democratised molecular biology. Well-equipped laboratories and a growing workforce of trained scientists now enable advanced biotechnology research to be carried out in a growing number of countries.

At the international level, the BWC has effectively prohibited the development, production, acquisition, transfer, stockpiling and use of biological and toxin weapons for 50 years. It currently has 189 States Parties, with only a number small of mostly minor states yet to sign or ratify the Convention[9]. However, the BWC has no authority over so-called non-state actors, such as terrorist groups or individual bio-terrorists.

[9] United Nations Office for Disarmament Affairs, *Biological Weapons Convention*, available at: https://disarmament.unoda.org/en/our-work/weapons-mass-destruction/biological-weapons/biological-weapons-convention (accessed 19 March 2026).

The BWC is often compared with the Chemical Weapons Convention (CWC), which similarly bans certain an entire class of weapons of mass destruction. The CWC entered into force in 1997 and now has 193 States Parties[10]. Its implementation is supported by a substantial international organisation: the Organization for the Prohibition of Chemical Weapons (OPCW), based in The Hague, Netherlands. By contrast, the BWC's Implementation Support in Geneva, Switzerland, has fewer than ten staff members. Moreover, unlike the CWC, the BWC has no formal verification regime for assessing purported breaches of the Convention, and also has no standing scientific advisory mechanism to assess emerging technologies.

A science advice mechanism

I titled this paper *The Double-edged Helix: DNA, Artificial Intelligence and the Biosecurity Challenge* and have so far examined the dual-use nature of biotechnology – that is, the fact that the manipulation of DNA can be used for beneficial purposes or, alternatively, with malicious intent. So far, however, artificial intelligence (AI) has not been addressed directly.

AI, in its many forms, is beginning to affect almost every aspect of our lives, from scientific research and medical diagnosis to art, music, and even the way football teams are trained to play. As with any powerful technology, however, its impact depends on how it is used. Like biotechnology, AI can be applied for harmful as well as beneficial purposes. In addition, there is growing concern that the combination of AI and biotechnology could provide malicious actors with 'short-cut' pathways to the development of biological weapons.

One illustration of this risk was presented in a recent publication (Urbina *et al*. 2022)[11]. The authors conducted a thought-experiment in which a commercial *de novo* molecular-design AI, normally used to propose new therapeutic drugs, was reconfigured to optimize for toxicity rather than safety. Among the structures proposed by the algorithm were

[10] The Chemical Weapons Convention www.opcw.org/chemical-weapons-convention (accessed 19 March 2026).

[11] Urbina, F., Lentzos, F., Invernizzi, C. and Ekins, S. (2022). Dual use of Artificial Intelligence-powered drug discovery. *Nat Mach. Intell.* 4(3): 189-191. pmc.ncbi.nlm.nih.gov/articles/PMC9544280/

several compounds resembling the highly toxic nerve agent, VX. Remarkably, within just six hours, the model generated more than 40,000 molecules exceeding the specified toxicity threshold, including compounds with previously unknown mechanisms of toxic action.

Because both biotechnology and AI are fast-moving fields with clear dual-use potential, there is widespread concern about the possible risks of their convergence.

At the same time, it is noted that the BWC currently lacks a formal science advisory mechanism. This raises a fundamental question: how can developments of such significance be assessed and communicated to State Parties in a timely and credible way to support informed decision-making?

Indeed, the BWC has been considering the establishment of a science advisory mechanism for some years. Many States Parties believe the time is ripe to create such a body, and although no country has formally opposed the idea, there is still debate about an appropriate and effective structure.

One proposal being considered favorably puts forward a *hybrid* model: an initial group of unlimited size, open to all, would discuss a topic, and this would be followed by a smaller expert group tasked with focusing on specific technical aspects of the topic. During 2023-2024, the InterAcademy Partnership (IAP)[12] conducted a proof-of-concept exercise to explore whether such a mechanism could function in practice. An open-ended online meeting was held in November 2023, followed by an invitation-only expert meeting in Trieste, Italy, in February 2024.

Between these two events, the question *to be taken under consideration by the smaller expert group was defined as: In the context of the BWC, what are the potential risks and benefits of the use of artificial intelligence*?

Following the exercise, IAP produced two reports: a technical report that analysed this question (IAP 2024a), and a procedural report that evaluated the effectiveness of the hybrid advisory process (IAP 2024b). IAP presented the findings during a webinar organized by the United Nations Institute for Disarmament Research (UNIDIR) and in-person in Geneva during the Fifth Session of the Working Group on Strengthening the BWC in December 2024.

[12] InterAcademy Partnership (IAP) is the global network of academies of science, medicine and engineering. Its ~150 member academies, working through 4 regional networks, provide access to some 30,000 leading scientists, engineers and health professionals in over 100 countries. www.interacademies.org

As detailed in the technical report, the mock scientific advisory body concluded that AI could provide important benefits, including:

- AI tools can monitor attempts to create a new pathogen, or to build a known high-risk pathogen, allowing controls to be put in place for biotechnology oversight.
- AI tools can test response capabilities, robustness of oversight mechanisms, and safety of biotechnology products and services.

However, the report also identified serious risks, including:

- AI tools may allow masking of illicit biotechnology activities.
- AI tools have raised concerns about enabling the development of novel (and potentially lethal) bioagents that may be difficult to detect without advanced capabilities, and about lowering barriers to access of toxic and/or pathogenic agents by both State and Non-State actors.

Responsible research practices

Given the uneven strength of regulatory frameworks across countries and the limited capacity of the BWC to keep pace with rapidly advancing science, how can the risk of accidental or deliberate misuse of biotechnology be reduced?

Here again, IAP has played an active role. Going back to 2012, it has produced a series of reports promoting responsible and ethical research practices, including:

- *Responsible Conduct in the Global Research Enterprise: A policy report* (IAP 2012)
- *Doing Global Science: A Guide to Responsible Conduct in the Global Research Enterprise* (IAP 2016)
- *The Tianjin Biosecurity Guidelines for Codes of Conduct for Scientists* (Johns Hopkins Center for Health Security *et al*. 2021)

The Tianjin Biosecurity Guidelines, in particular, focus on preventing the intentional misuse of bioscience in line with the objectives of the BWC, while also addressing the prevention of the unintentional harm. They are based on the principle that all scientists share responsibility for strengthening biosecurity and minimising risks. Available in all official UN languages, the Guidelines articulate ten core principle covering:

1) Ethical Standards
2) Laws and Norms

3) Responsible Conduct of Research
4) Respect for Research Participants
5) Research Process Management
6) Education and Training
7) Research Findings Dissemination
8) Public Engagement on Science and Technology
9) Role of Institutions
10) International Cooperation

Together with its partners – the Center for Biosafety Research and Strategy at Tianjin University (China) and the Johns Hopkins Center for Health Security (USA) – IAP has proposed that the BWC formally endorse these principles (Gronvall *et al*. 2022)[13] However, it is clear that multilateral (UN) agreements alone are not sufficient to regulate or oversee all potential breaches of biotechnology governance.

In addition to such 'top down' approaches, therefore, a complementary *bottom-up* approach is also essential. Each new generation of scientists must be educated in biosecurity, ethics and responsible research practice, beginning during the undergraduate and postgraduate training and continuing throughout their careers. As emphasized in the Tianjin Biosecurity Guidelines, universities and research centers should also develop and implement their own institutional codes of conduct. Here, academies of science can play a facilitating role – especially in developing countries – by promoting, harmonizing and disseminating best practices across institutions.

Ultimately, it is up to *all of us* – through education and training, and the leadership of scientific institutions – to stand up for what is right and ensure that biological weapons are consigned to history.

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[13] Gronvall, G.K., Wang, L., McGrath, P.F. *et al* (2022). *Trends in Microbiology*. The Biological Weapons Convention should endorse the Tianjin Biosecurity Guidelines for Codes of Conduct https://www.interacademies.org/publication/biological-weapons-convention-should-endorse-tianjin-biosecurity-guidelines-codes

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